Neutrino Physics, Planning for the Future. (LBNF/DUNE in the US)

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University of Campinas
Brazil. May 11, 2016

My Thanks to Sociedade Brasileira de Física (SBF) and the American Physical Society (APS)

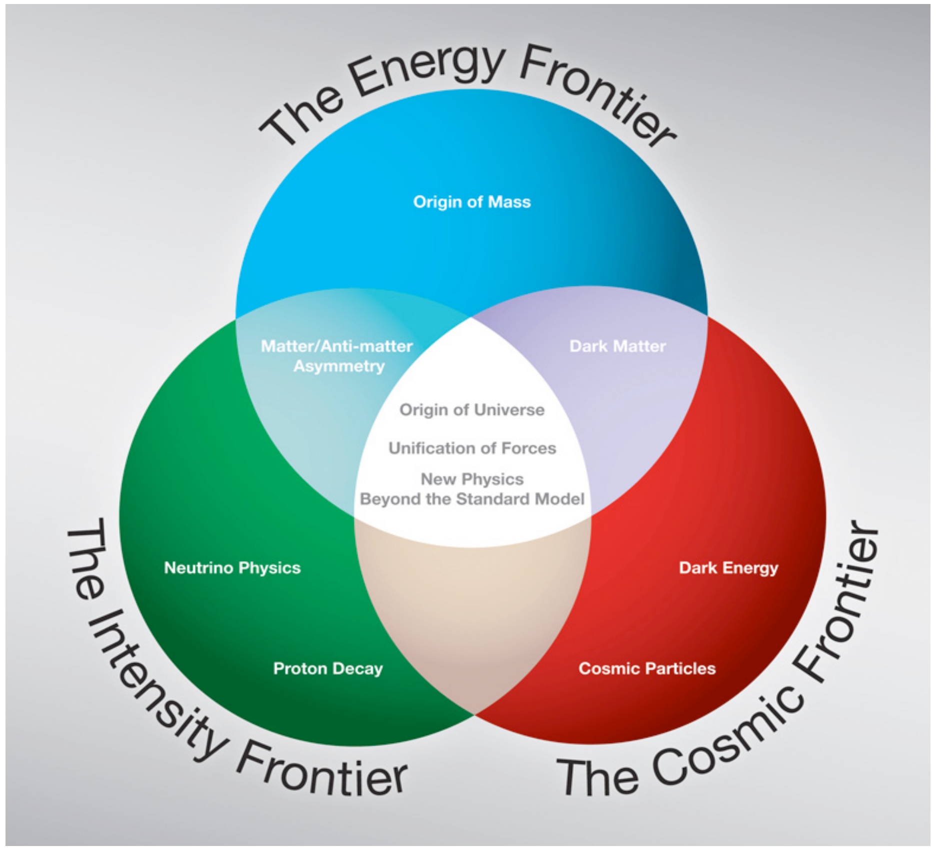
BROOKHAVEN
NATIONAL LABORATORY

Outline

- **Brief review of neutrino physics.**
- **The case for a new accelerator beam experiment**
- **Physics Sensitivity**
- **LBNF/DUNE project description**
  - **Fermilab Accelerator/Beam**
  - **Near Detector**
  - **Far Detector**
- **Project Status**

I will highlight challenges that need to be resolved during the seminar. These will be marked with a ☼

Islands of discovery

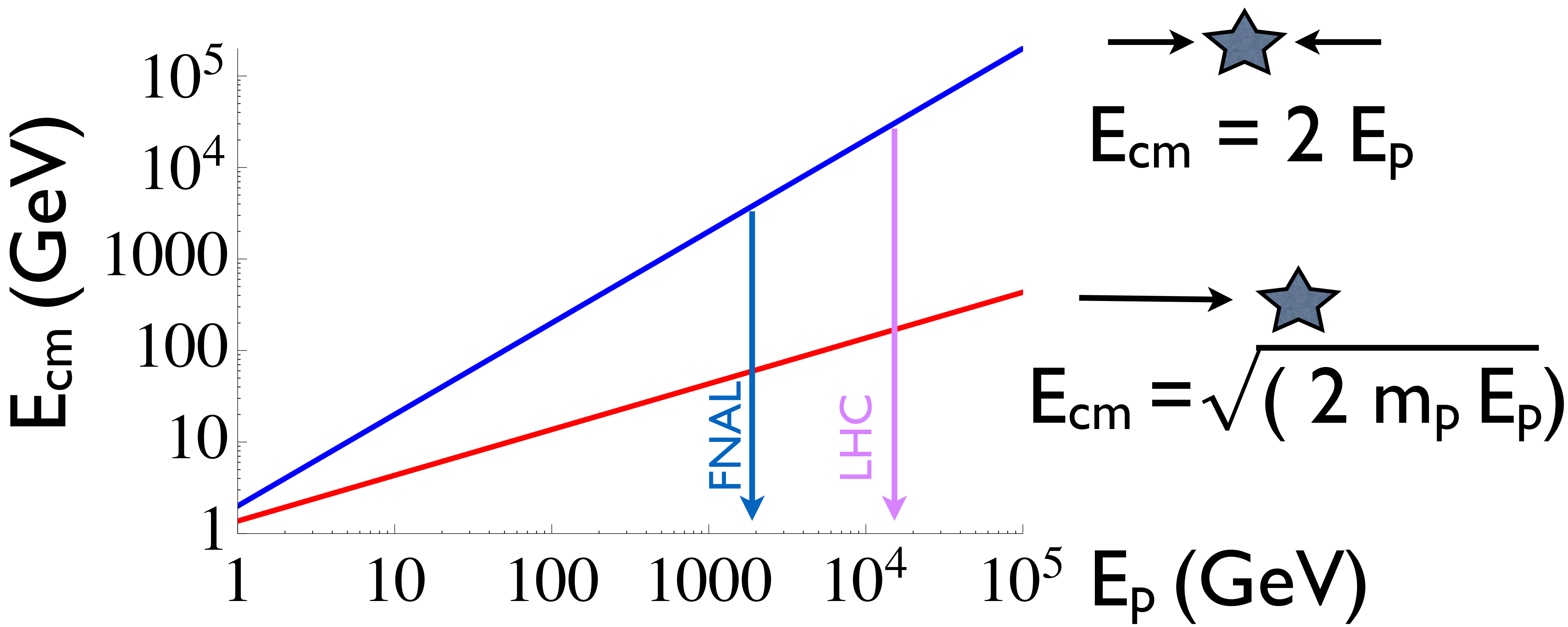


US view of fundamental particle physics

Problem	Key observations	Tools
Dark matter/Dark Energy	Velocity curves/ Accelerating Universe/direct detection	Astronomical surveys/underground det/colliders
Neutrino Mass/ mixing	Neutrino oscillations/ 0vbb/beta-decay	Underground Neutrino det./beam/ spectrometers
Matter/antimatter asymmetry (BAU)	CP violation Baryon/lepton num.	K and B decay,neutrino beam,proton/mu decay
Three generations	Quark mixing Neutrino mixing	K and B mesons Neutrino Beams underground det. Colliders
Unitarity at the TeV scale	Higgs particle	Collider/Detectors, EDM, rare decays

- There must be a pattern to these seemingly disconnected discoveries and we need to collect all parts of the puzzle.

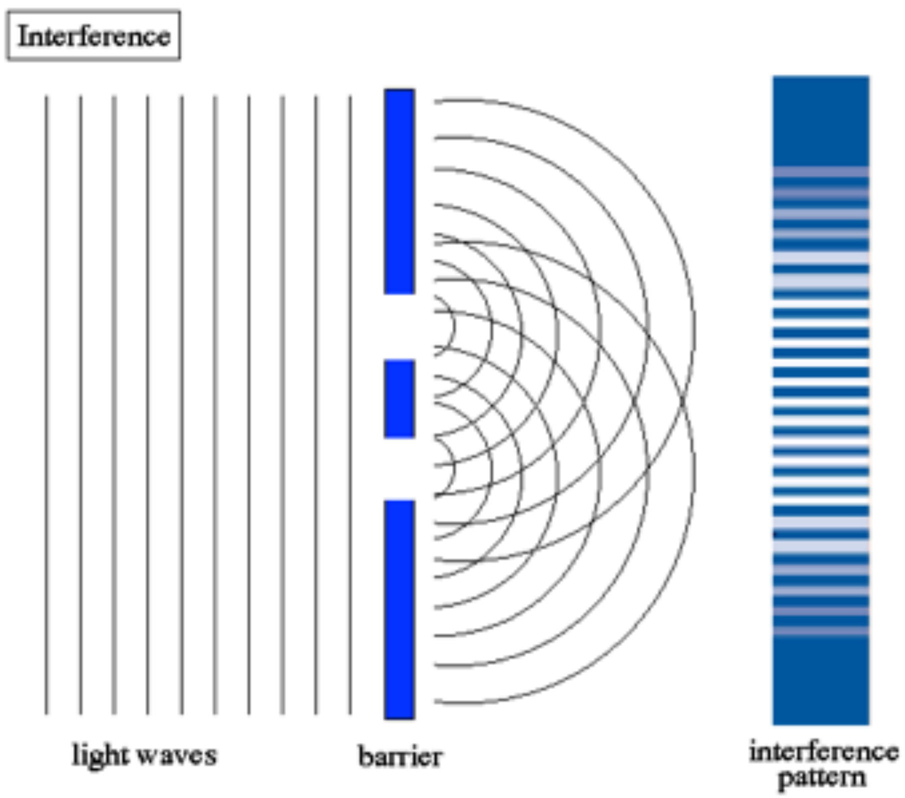
The collider technique

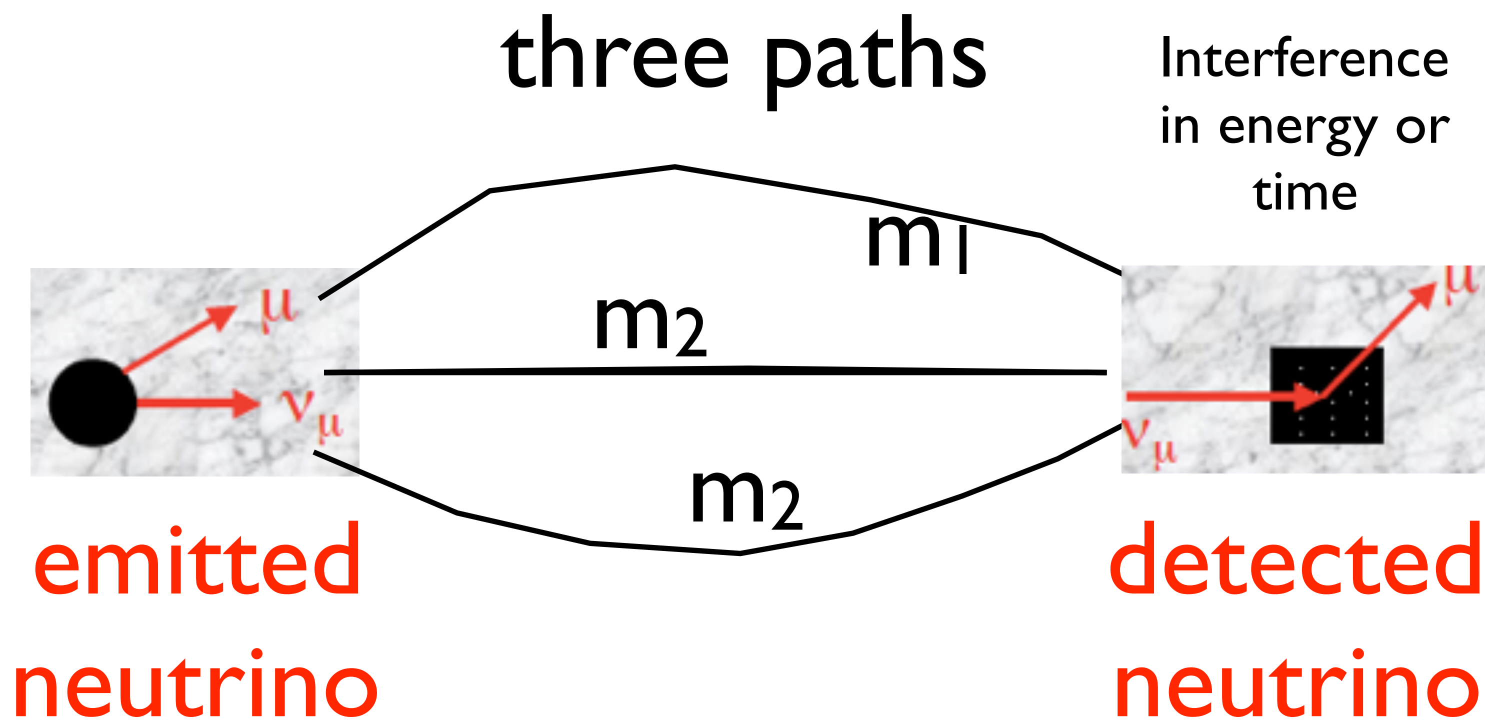


- **The technique for making new particles had an extraordinary advance in ~1970s. The collider technique allowed several magnitude increase in available energy. Thus Tevatron and the LHC !**

- **There is no technological barrier to a 200 TeV collider.**

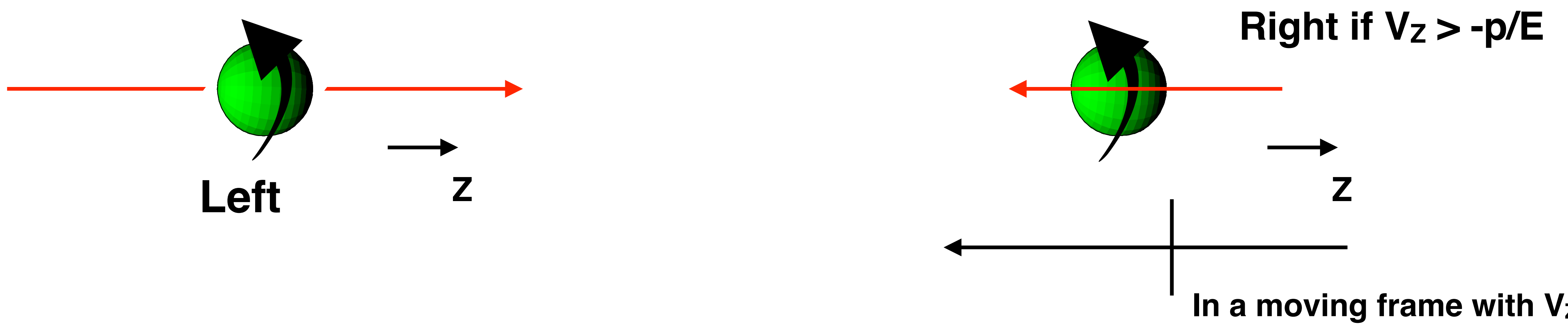
Neutrino Oscillations Represent a new advance





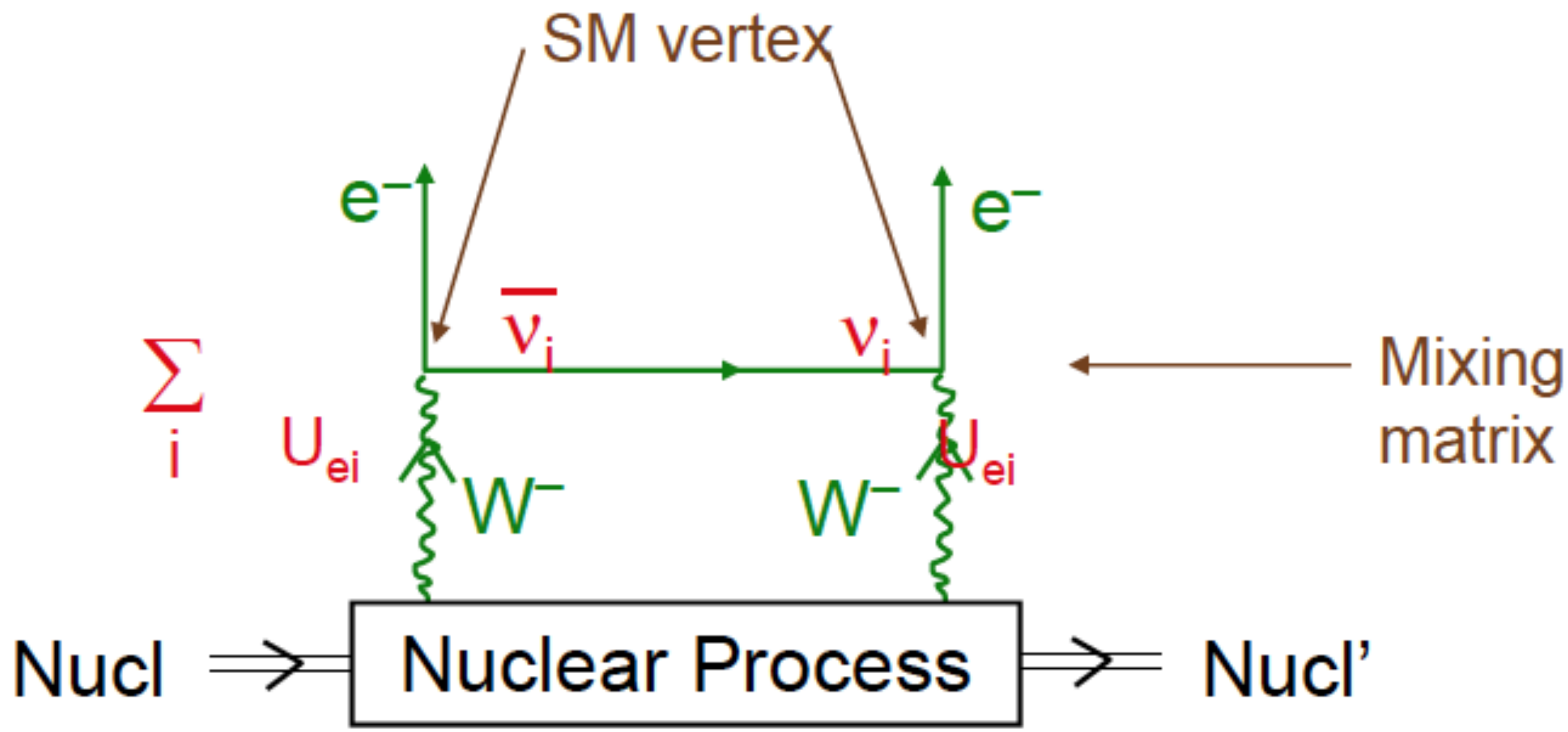
- Just as classic optical interferometry has led to new precision, neutrino interferometry has potential to be sensitive to new scales. We do not yet know the full implications.
- e.g. Measure extremely small masses or interactions. The sensitivity depends only on Length/Energy of the neutrinos.

Importance of neutrino mass



- In the standard model only ν_L interacts with matter, ν_R does not interact. Since neutrinos are produced in weak interactions only, ν_R do not exist.
- Handedness and Helicity are identical if particles are massless.
- Particles with mass can be transformed to opposite helicity by a Lorentz transformation.
- **Since massive neutrinos have no charge, is anti-ν_L == ν_R ?** This would simplify our understanding and also lead to Lepton-Number violation.

0-neutrino double beta decay



- Only practical way to test for Majorana (are neutrinos their own anti-particles ?) nature.
- Amplitude must be $\propto (G_F)^2$ therefore rate will be very small compared to ordinary beta decay which has amplitude of G_F.
- In the decay a right-handed antineutrino is emitted and then a left-handed neutrino is absorbed. The RH neutrino has a LH projection only if it has a small mass ⇒ Amplitude must be $\propto m_\nu/E$
- Therefore 0nuDBB is sensitive to Majorana neutrino mass which can be reachable if the mass ordering is inverted.

Theoretical musings

- Relations: neutrinos-other phenomena, neutrino parameters, physics behind neutrino mass, theory of flavor, unification.
- Ultimate goal is to understand quarks/leptons/generations. It is unclear at the moment, but the new neutrino data combined with quark data has provided a huge boost to the effort. quarks-leptons talk to each other !
- Consensus that there are now well motivated (SUSY) GUT models with:
  - charge quantization, anomalies, quark/lepton quantum numbers, unification of gauge couplings
  - Small neutrino masses, large or maximal neutrino mixing (crucial new data)
- What do you get out ?
  - Proton decay !
  - Leptogenesis !
  - Predictions for relationships between masses and mixings !

Bottom up approach: key observation is the large and perhaps maximal neutrino mixings

$$U_{MNSP} = U^{\dagger}_{CKM} \; T$$

from Majorana Physics (two large angles, $\theta_{13} = 0$)

Quark/Lepton mixings

Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)	Sum
θ_{12}	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$	46.6
θ_{23}	38 +3-1	$2.38 \pm 0.06^\circ$	40.4
θ_{13}	$8.9 \pm 0.5^\circ$	$0.201 \pm 0.011^\circ$	9.1
δm^2	$+(7.54 \pm 0.22) \times 10^{-5}$ eV^2		
$\lvert\Delta m^2\rvert$	$(2.43^{+0.10}_{-0.06}) \times 10^{-3}$ eV^2	$m_3 >> m_2$	
δ_{CP}	$-170 \pm 54^\circ$	$67 \pm 5^\circ$	

☞ • $M_{seesaw} \sim M_{GUT}$

Perhaps a signal of Q-L grand unification:

• $\theta^{\nu}_{12} + \theta^{q}_{12} \simeq 45^o$; $\theta^{\nu}_{23} + \theta^{q}_{23} \simeq 45^o$; (Called (QLC))

Smirnov; Raidal; Minakata and Smirnov

$\sin^2\theta_{13} \sim \frac{1}{2} \sin^2\theta_C$

Tantalizing hints (but lack of clarity) need to be explored with more precise and comprehensive measurements.

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For 3 Active neutrinos.

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

(Double β decay only)

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\checkmark} \cdot \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}}_{?} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{\checkmark} \cdot \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\checkmark} \cdot \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}}_{?}$$

Atmospheric, Accel. | **CP Violating Phase** | **Reactor, Accel.** | **Solar,Reactor** | **Majorana CP Phases**

Range defined for Δm_{12}, Δm_{23} ✓

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\frac{\Delta m^2 L}{E})$$

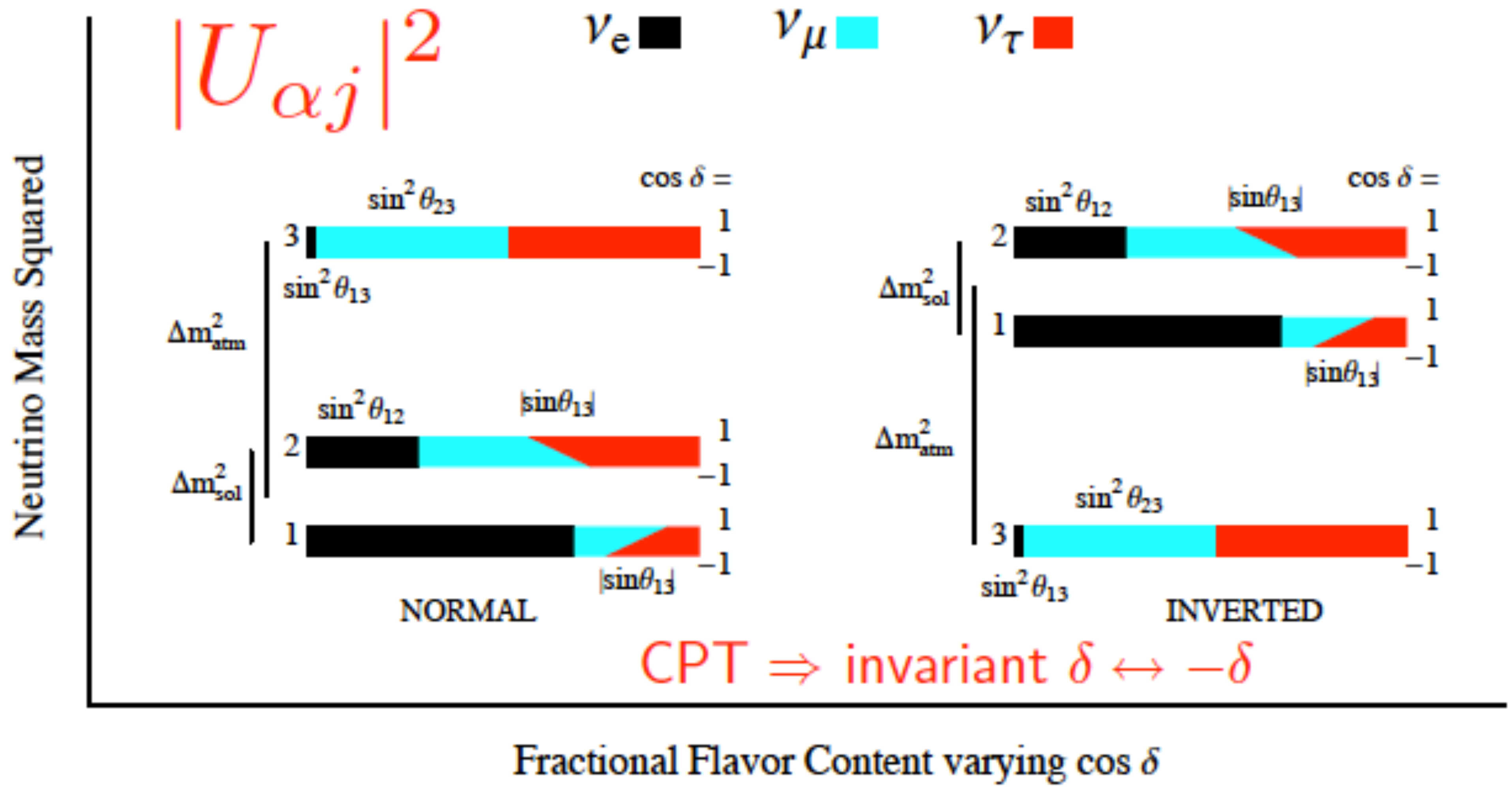
CP Violating Phases: implication for Antimatter/Matter asymmetry via Leptogenesis?

Assemble the best picture and ask more questions

$\theta_{23} \sim \pi/4$

$\theta_{12} \sim \pi/6$

$\theta_{13} \sim \pi/20$



- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$

Credibility of leptogenesis

- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$

Impacts GUT models

- What is the neutrino mass hierarchy? $(\Delta m^2_{13} > 0?)$

Observability of double beta decay, and the problem of generations.

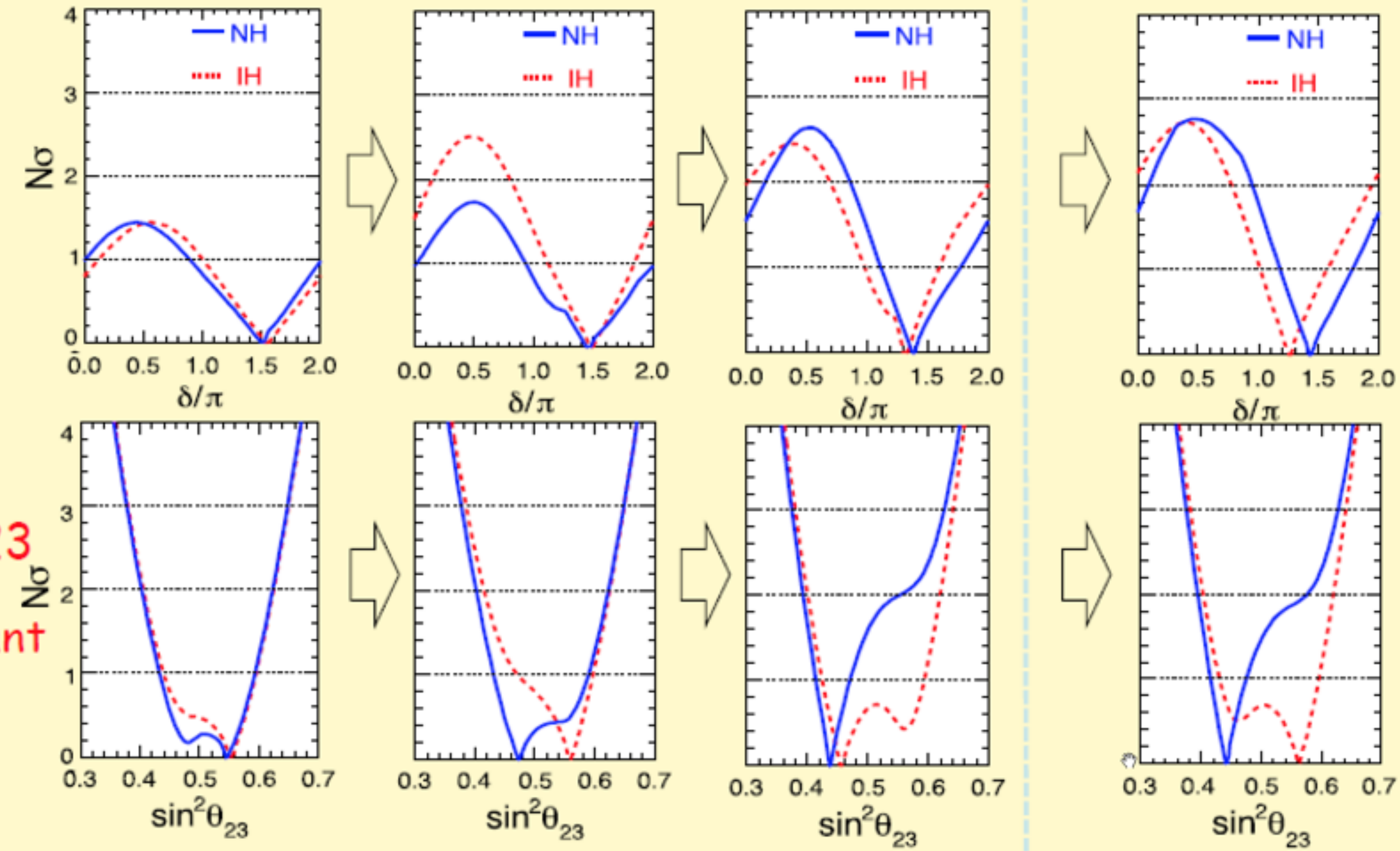
Recap on δ, θ_{23}, $\Delta\chi^2$(IH-NH)

pre-ν2014 | post-ν2014

LBL+Sol+KL | +SBL Reac | +SK atm | +Daya Bay'14 (prelimin.)

δ

θ_{23} octant

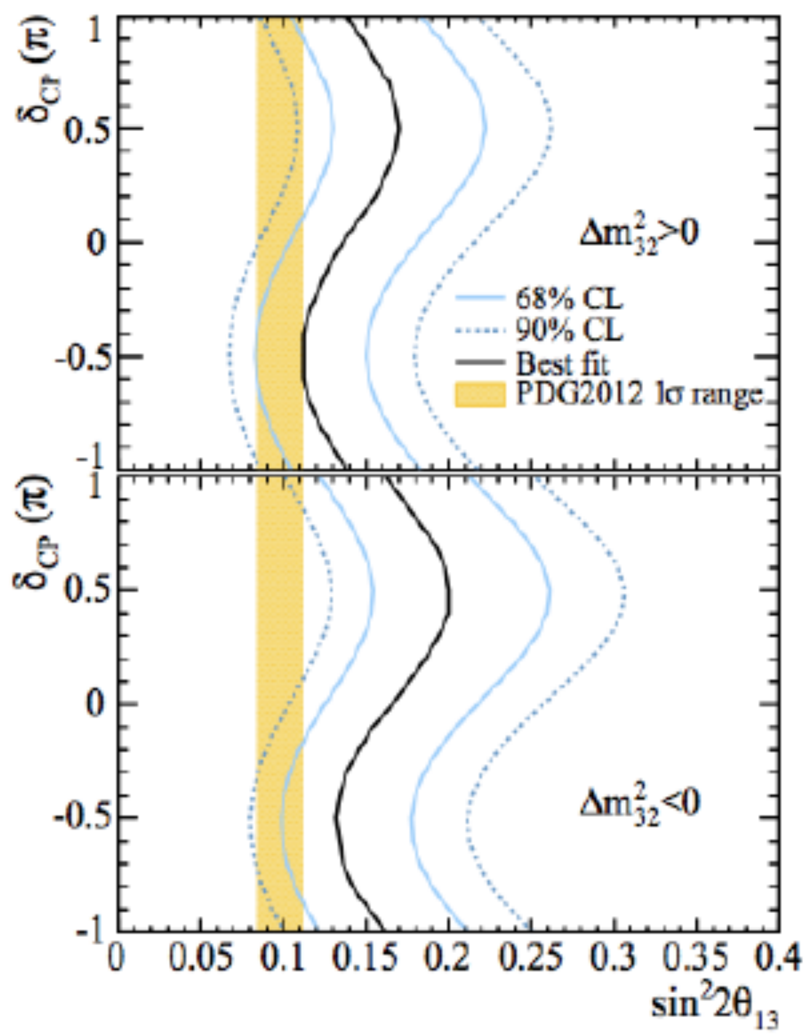


intriguing, sin δ < 0 favored

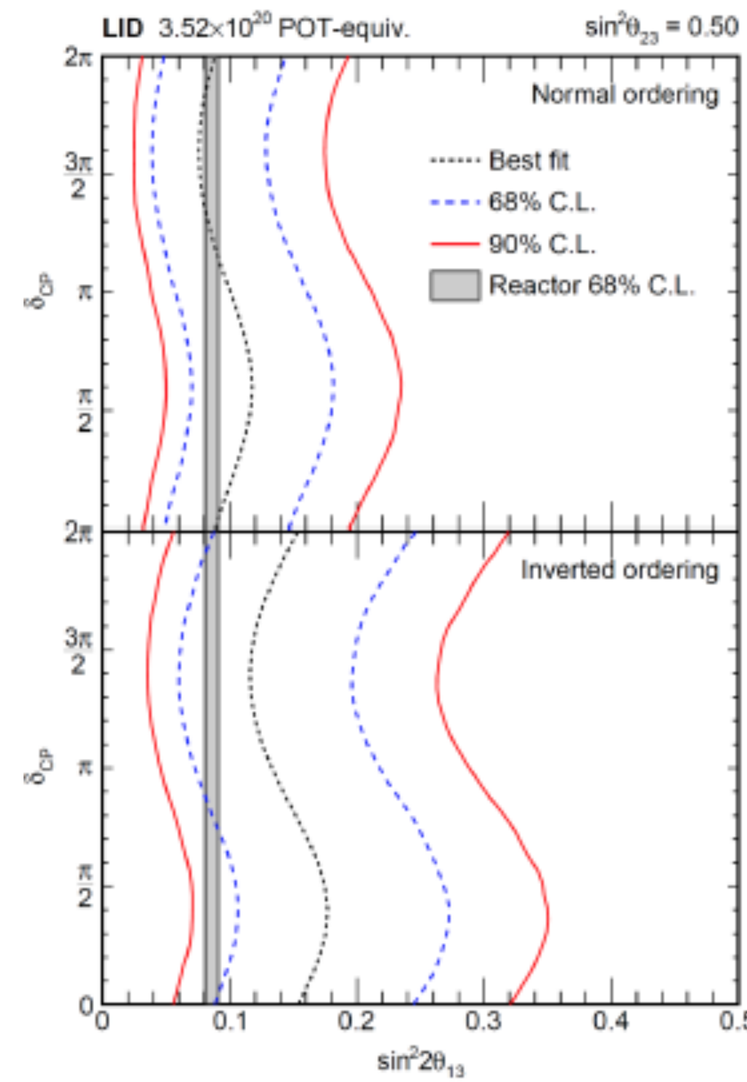
unstable, fragile

$\Delta\chi^2$ (IH-NH): -1.4 ⇨ -1.1 ⇨ -0.3 ⇨ -0.1

irrelevant



T2K(Phys.Rev.D88 (2013) 3,032002)
measures a combination of θ13 and δCP while
reactors (PDG 2012) measure pure θ13 effects.
Their combination favors δCP = - π/2

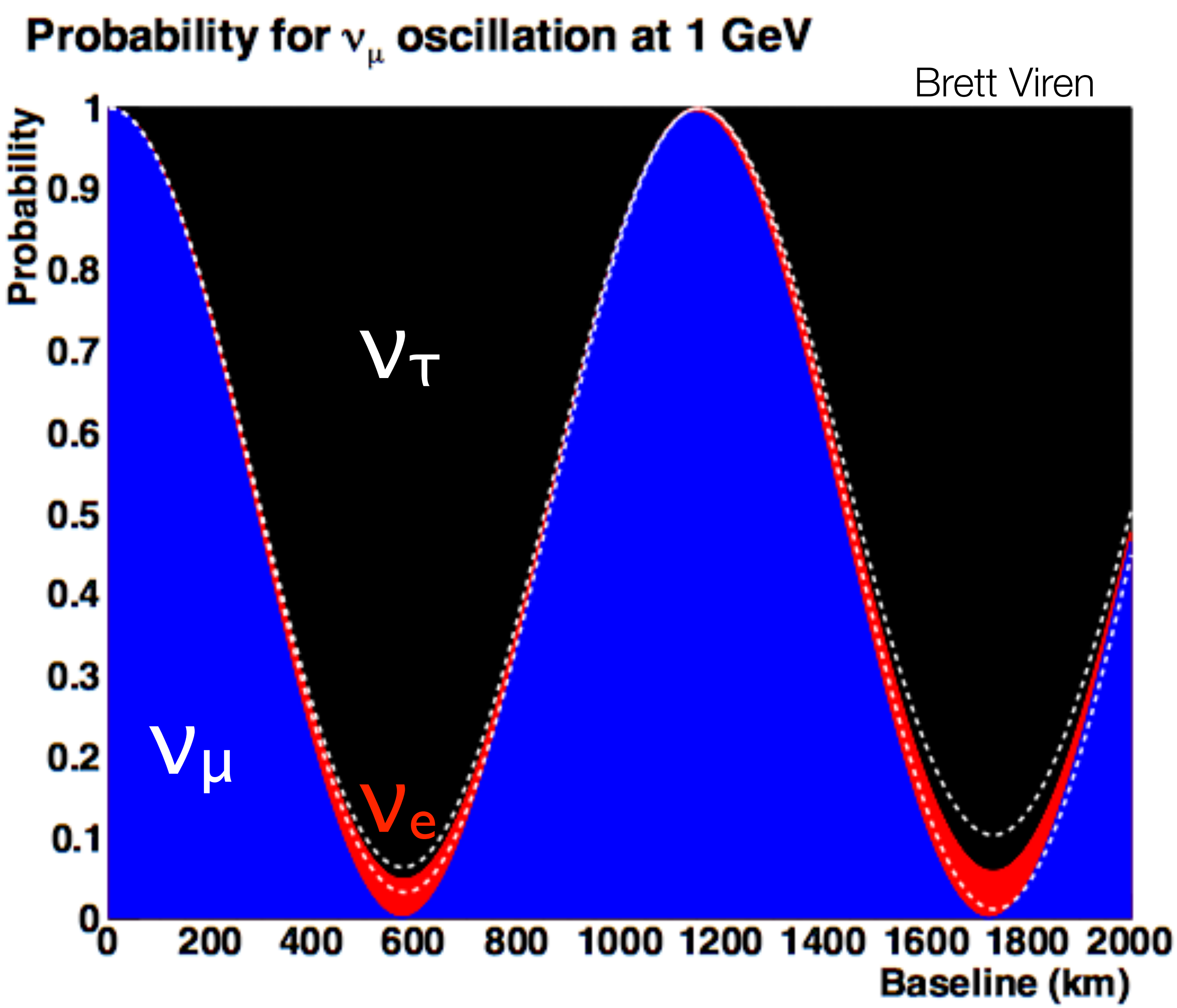


Nova, 7.6% of full statistics (LP2015)

In effect the accelerator experiments are seeing a robust signal of electron neutrino events, forcing preference for CP phase of -π/2.

T2K has also now observed 3 events in anti-neutrino mode.

The full picture of the oscillation effect starting with pure muon type neutrino.



Dashed white lines correspond to CP violation or the unknown phase.

Notice that for sizable effects one needs long distances and large energies.

- **There are precise predictions:**
  - **Large Matter Effects (not yet seen in a laboratory experiment)**
  - **Potentially large CP violation (not yet seen)**
  - **We should measure this picture with a detailed spectrum. We need to measure electron and muon type of neutrinos at high energies.**

Discussion over future program

- The success of Super-Kamiokande was the catalyst for new discussion on a very larger underground detector and its scientific potential. Started in 1999.

- If coupled to an accelerator muon neutrino beam, such a detector and beam project would be highly motivated. But the scale has to be huge.

- Physics motivation is CP violation in neutrinos, proton decay, and neutrino astrophysics.
- Accidentally: the size of detector needed for both CP violation and next steps in proton decay are roughly the same. The detector requirements are also the same !
- We realized that we could start the planning of this with little risk because the scale was independent of the value of θ_{13}.

Extra Long Baseline Neutrino Oscillations and CP Violation

William J. Marciano
Brookhaven National Laboratory, Upton, NY 11973

August 22, 2001

2001

The potential for studying CP violation in neutrino oscillations using conventional ν_μ and $\bar{\nu}_\mu$ beams is examined. For $\Delta m^2_{21} << \Delta m^2_{31}$ and fixed neutrino energy, E_ν, the CP violating asymmetry $A \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)/P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in vacuum is shown to be measurable with roughly equal maximal statistical precision at distances $L_n \simeq (2n+1)\left(\frac{2\pi E_\nu}{\Delta m^2_{31}}\right), n = 0, 1, 2 \ldots$

Neutrino Oscillation Experiments for Precise Measurements of Oscillation Parameters and Search for $\nu_\mu \to \nu_e$ Appearance and CP Violation.

LETTER OF INTENT to Brookhaven Nation[...]ry.

2002

D. Beavis, M. Diwan, R. Fernow, J. Gallardo, S. Kahn, H. Kirk, W. Marciano, W. Morse, Z. Parsa, R. Palmer, T. Roser, N. Samios, Y. Semertzidis, N. Simos, B. Viren, W. Weng
Brookhaven National Laboratory Box 5000, Upton, NY 11973-5000

W. Frati, J.R. Klein, K. Lande, A.K. Mann, R. Van Berg and P. Wildenhain
University of Pennsylvania Philadelphia, PA 19104-6396

R. Corey
South Dakota School of Mines and Technology Rapid City, S.D. 57701

D.B. Cline, K. Lee, B. Lisowski, P.F. Smith
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095 USA

Very Long Baseline Neutrino Oscillation Experiment for Precise Measurements of Mixing Parameters and CP Violating Effects

2003

M.V. Diwan, D. Beavis, Mu-Chun Chen, J. Gallardo, R.L. Hahn, S. K[...] W. Marciano, W. Morse, Z. Parsa, N. Samios, Y. Semertzidis, B. Viren, W. We[...] M. Yeh
Physics Department, Brookhaven National Laboratory, Upt[...]

W. Frati, K. Lande, A.K. Mann, R. Van Berg, P. Wildenhain
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104

J.R. Klein
Department of Physics, University of Texas, Austin Texas 78712

I. Mocioiu
Physics Department, University of Arizona, Tucson, AZ 85721

R. Shrock
C. N. Yang Institute for Theoretical Physics, State University of New York, Stony Brook, NY 11794

K.T. McDonald
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544

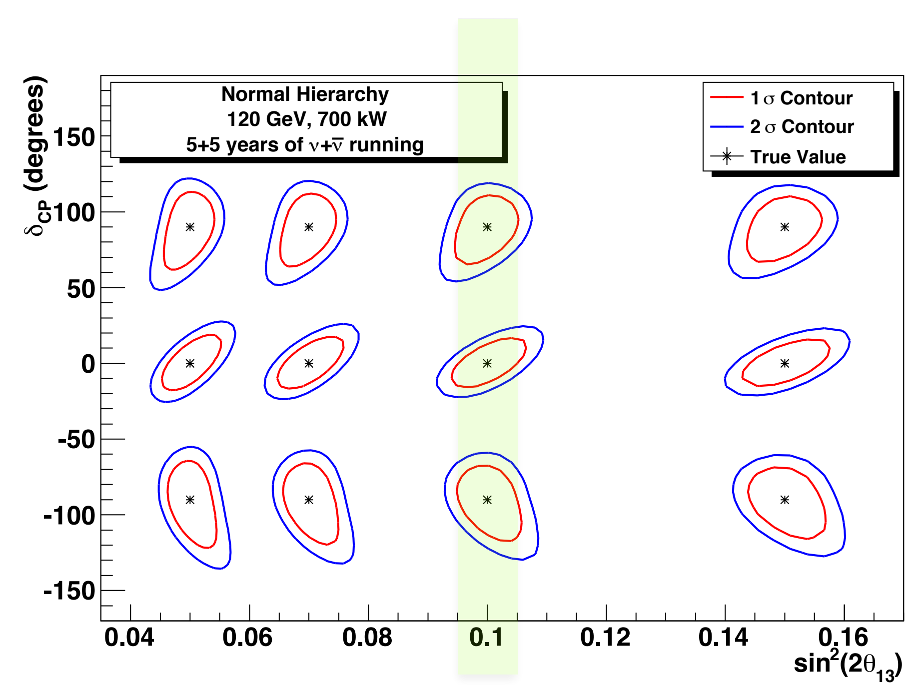
The Case for a Super Neutrino Beam

2004

Milind V. Diwan
Brookhaven National Laboratory

arxiv:0407047

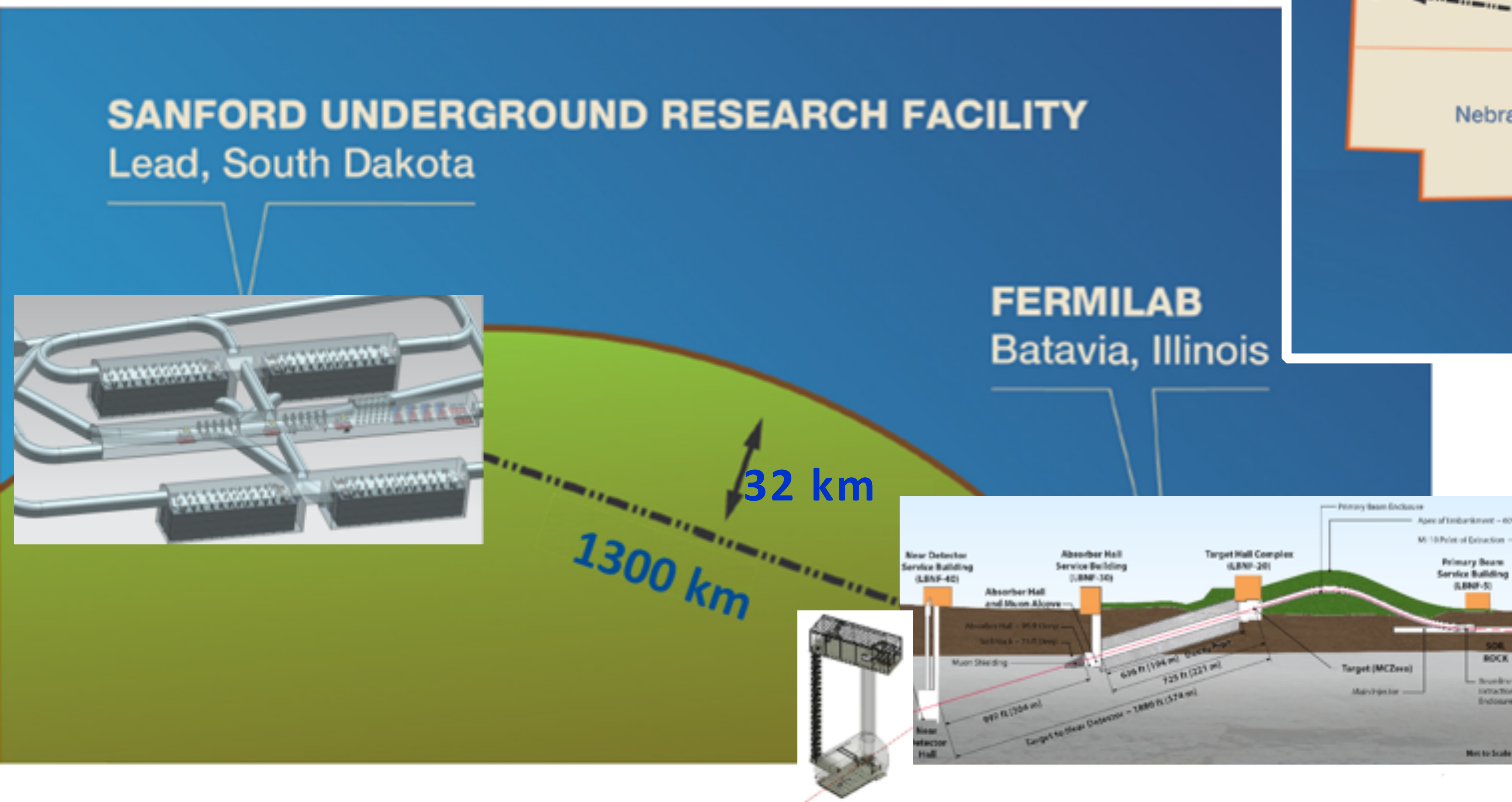
Examination of baselines and systematics



Key elements for the program

- **The scale of the program to first order is not dependent on θ_{13}~9deg.**
- **Roughly independent of length also, but needs to be long enough for resolving mass ordering.**
- **Must have a broad-band beam.**
- **One must have a very large detector: (500kt water, ~100kt of LAr) for statistics.**
- **For a fine grained detector use the inclusive cross section to gain statistics.**

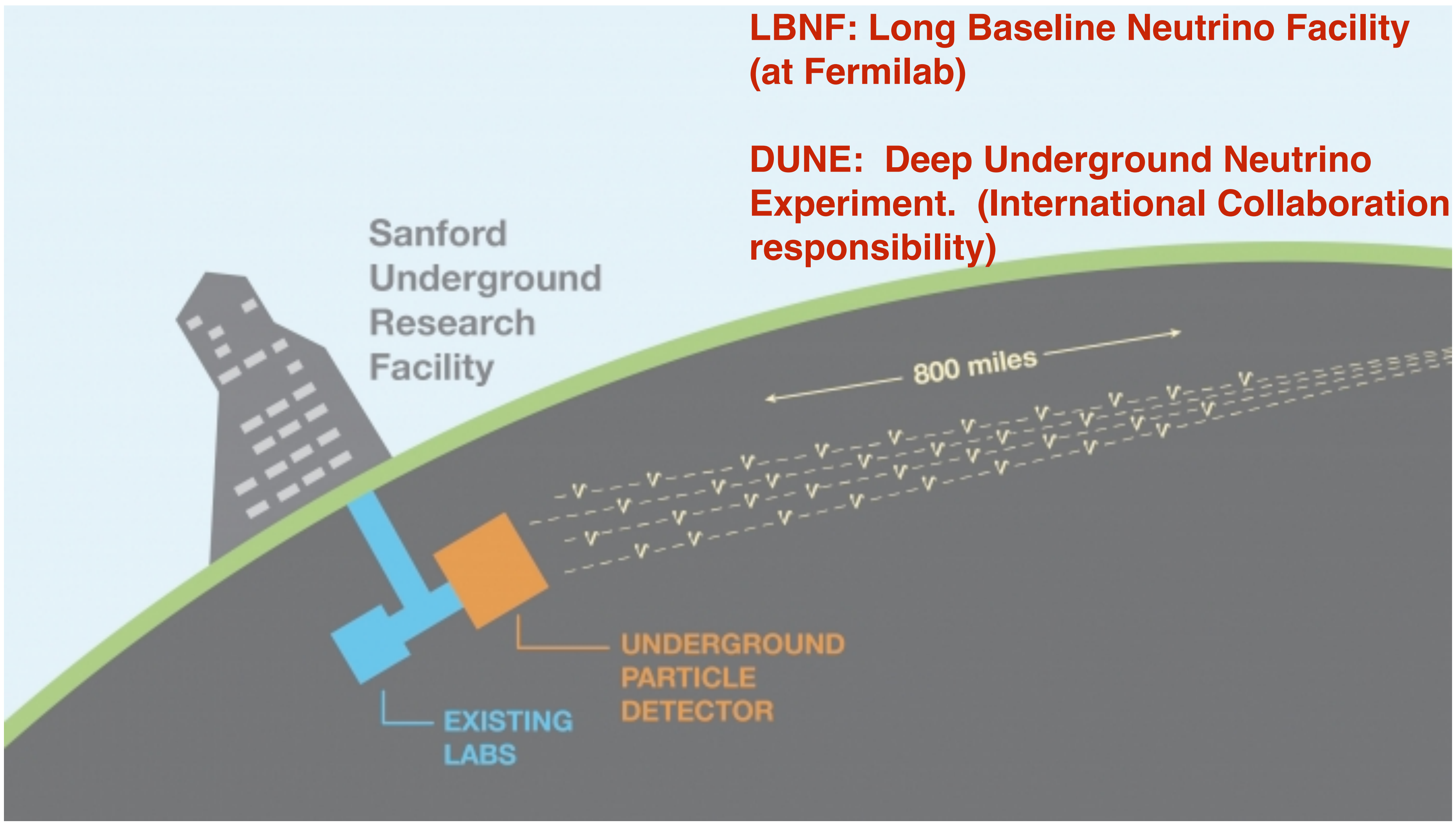
The Next-Generation Long-Baseline Experiment: LBNF / DUNE



- Comprehensive experimental program to determine CP violation, Mass Hierarchy, and make precision measurements of oscillation parameters
- Astrophysical neutrinos and proton decay with Far Detector
- Precision neutrino scattering measurements with Near Detector

P5

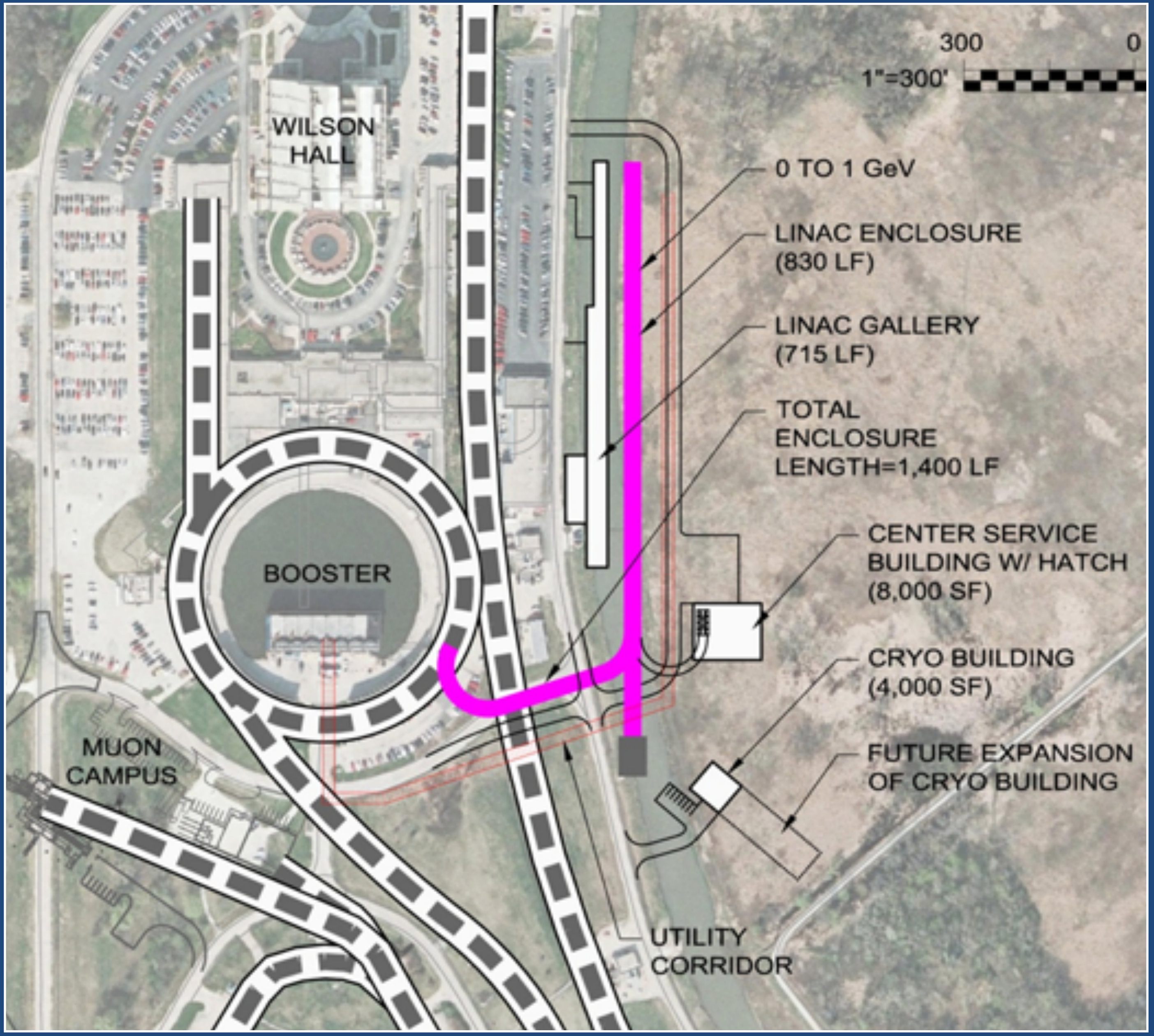
Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.



The previous scientific collaborations have been transformed into a new global collaboration with many more international partners. It now has >700 members with 143 institutions. The collaboration will proceed with the US based configuration.

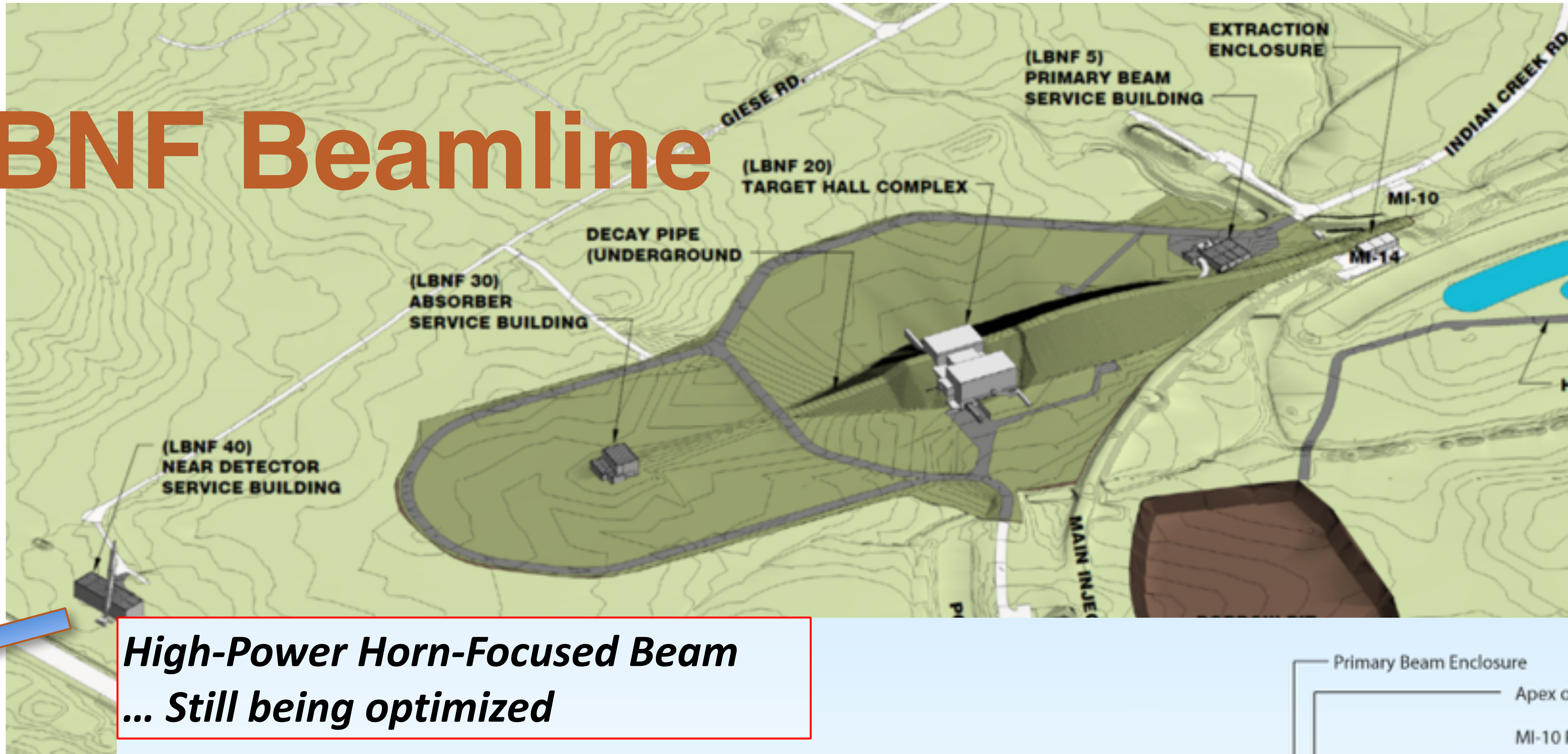
Proton-Improvement-Plan Phase II (PIP-II)

- Replace existing 400 MeV linac with a new 800 MeV superconducting Linac
- 1.2 MW beam power to LBNF at start-up of experiment.
- Plan is based on well-developed superconducting RF technology with international partnerships.
- Strong support from DOE and in the recent Prioritization Panel report.
- Flexible design - future upgrades could provide > 2MW to LBNE.



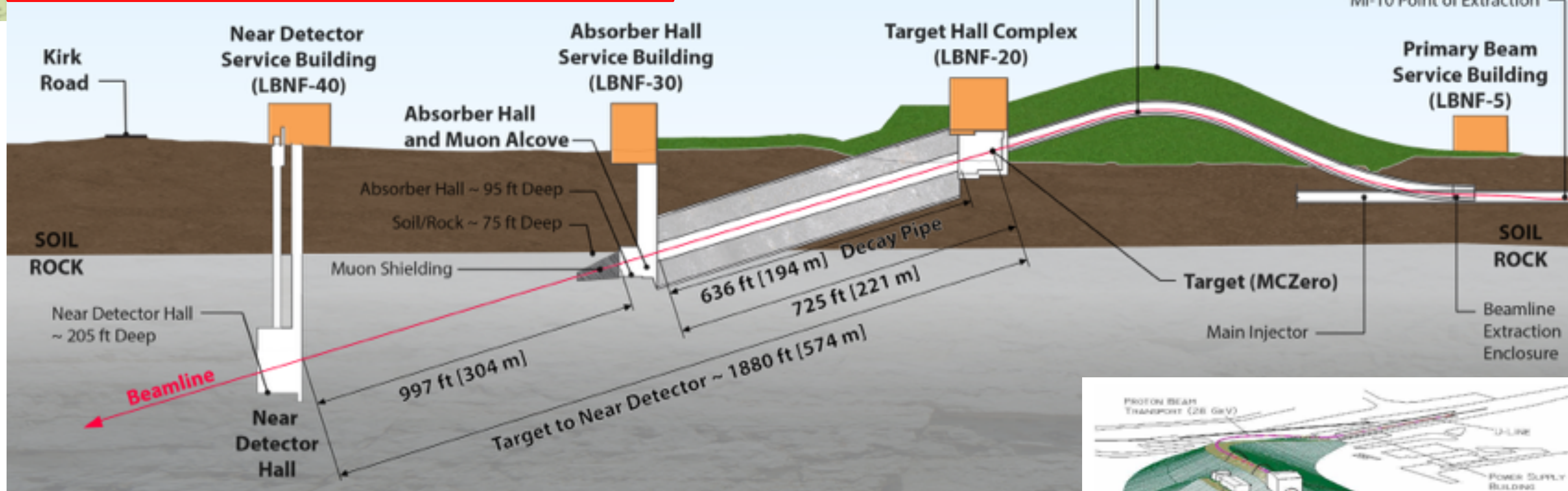
Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

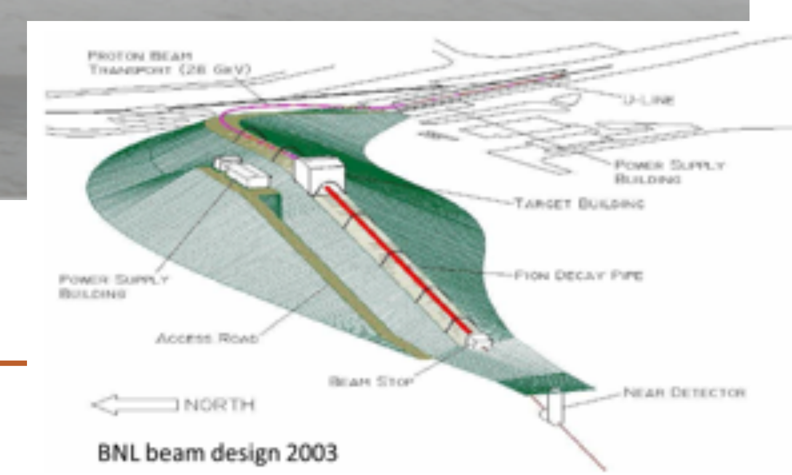
LBNF Beamline



To SURF

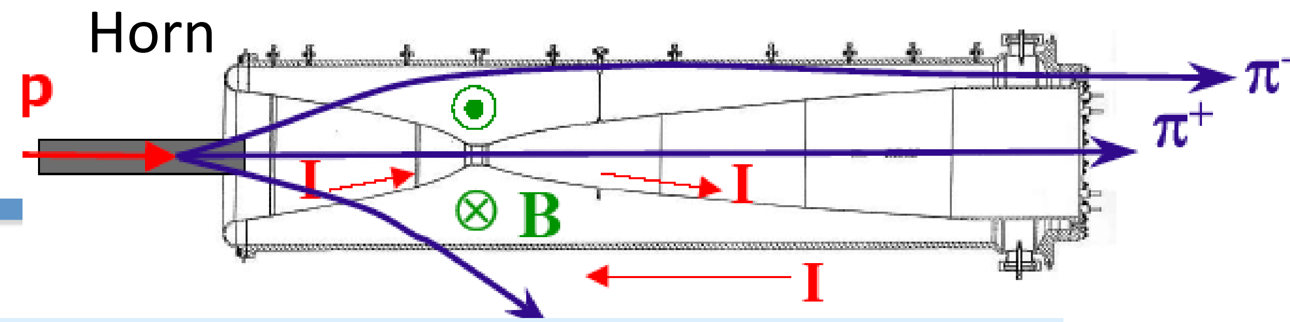
High-Power Horn-Focused Beam
… Still being optimized

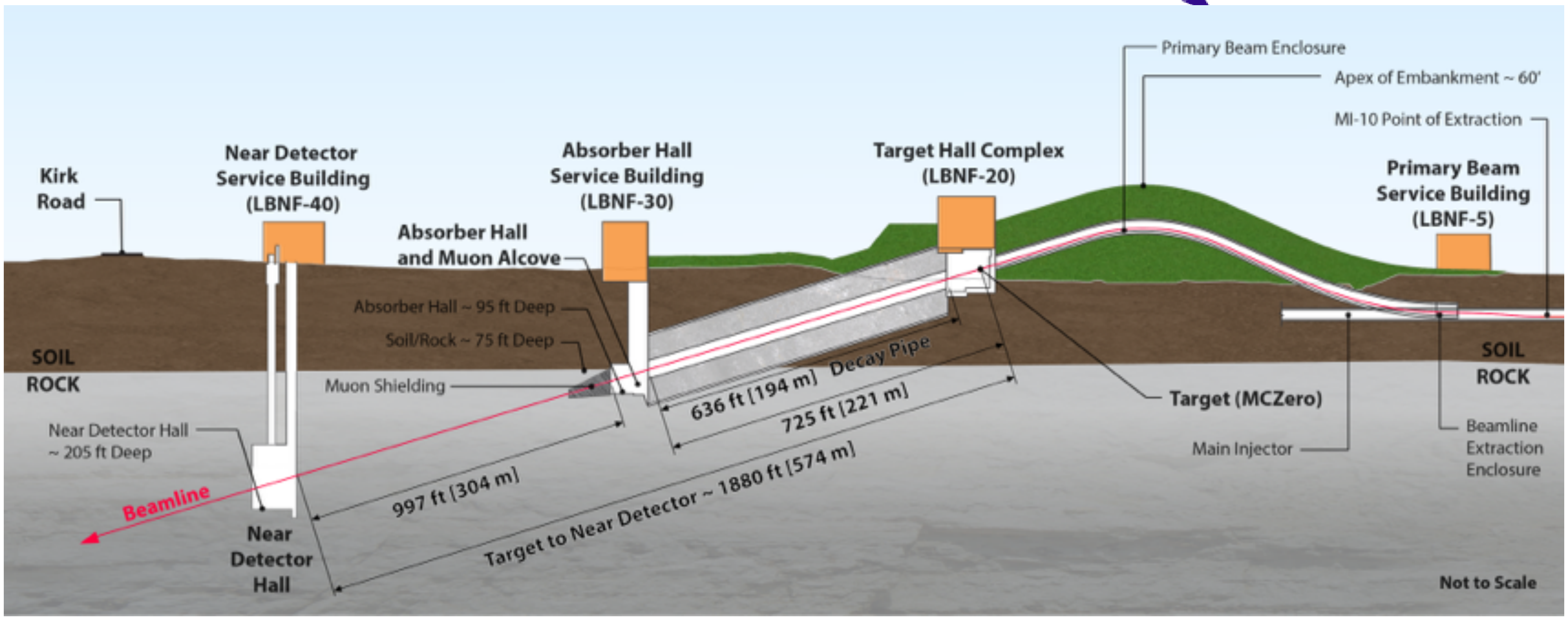


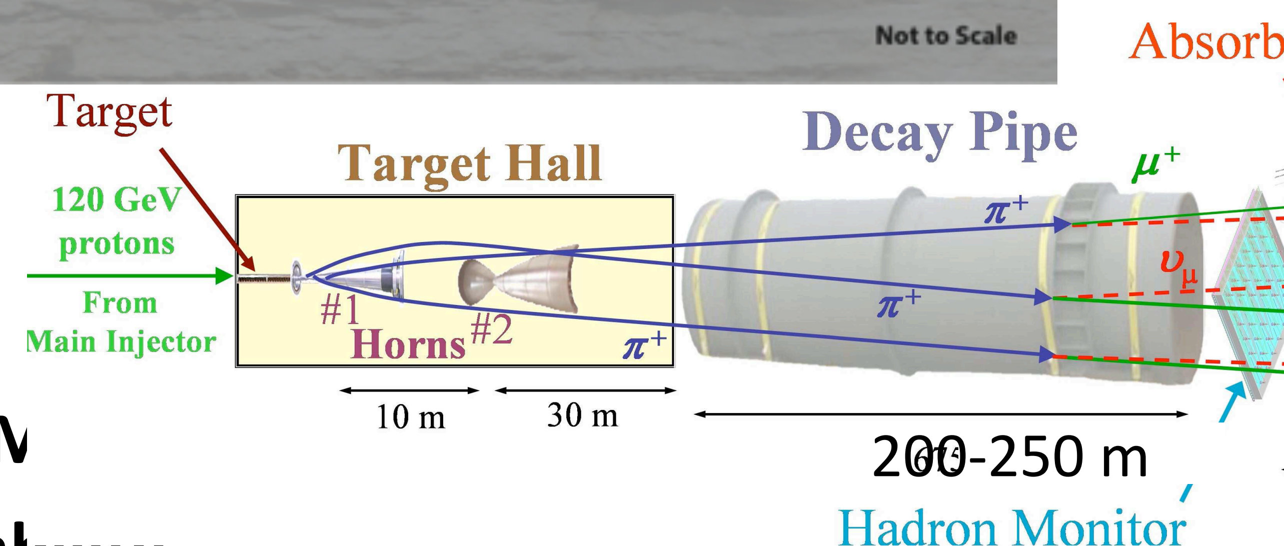


BNL beam design 2003

LBNE Neutrino Beamline



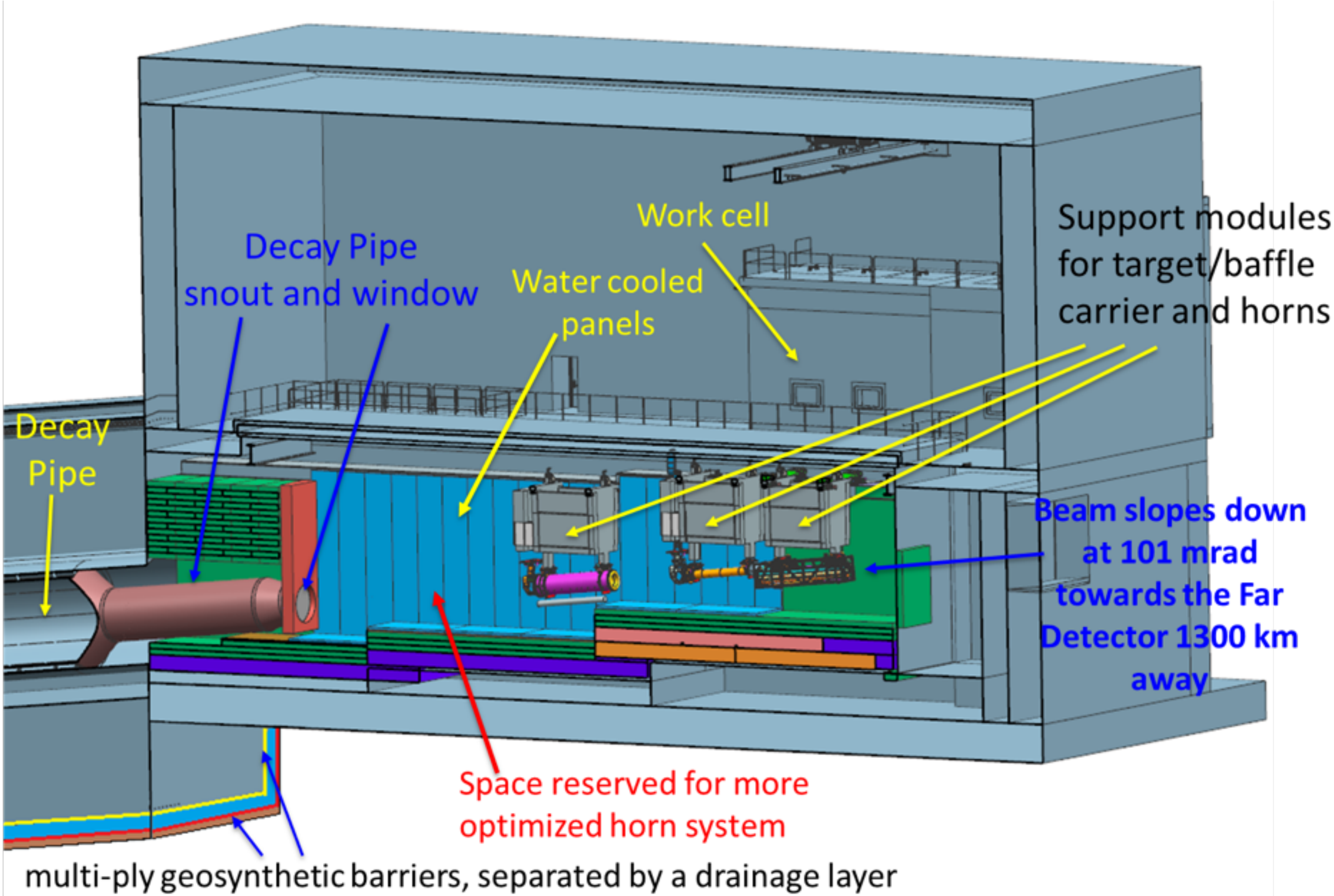




Proton beam

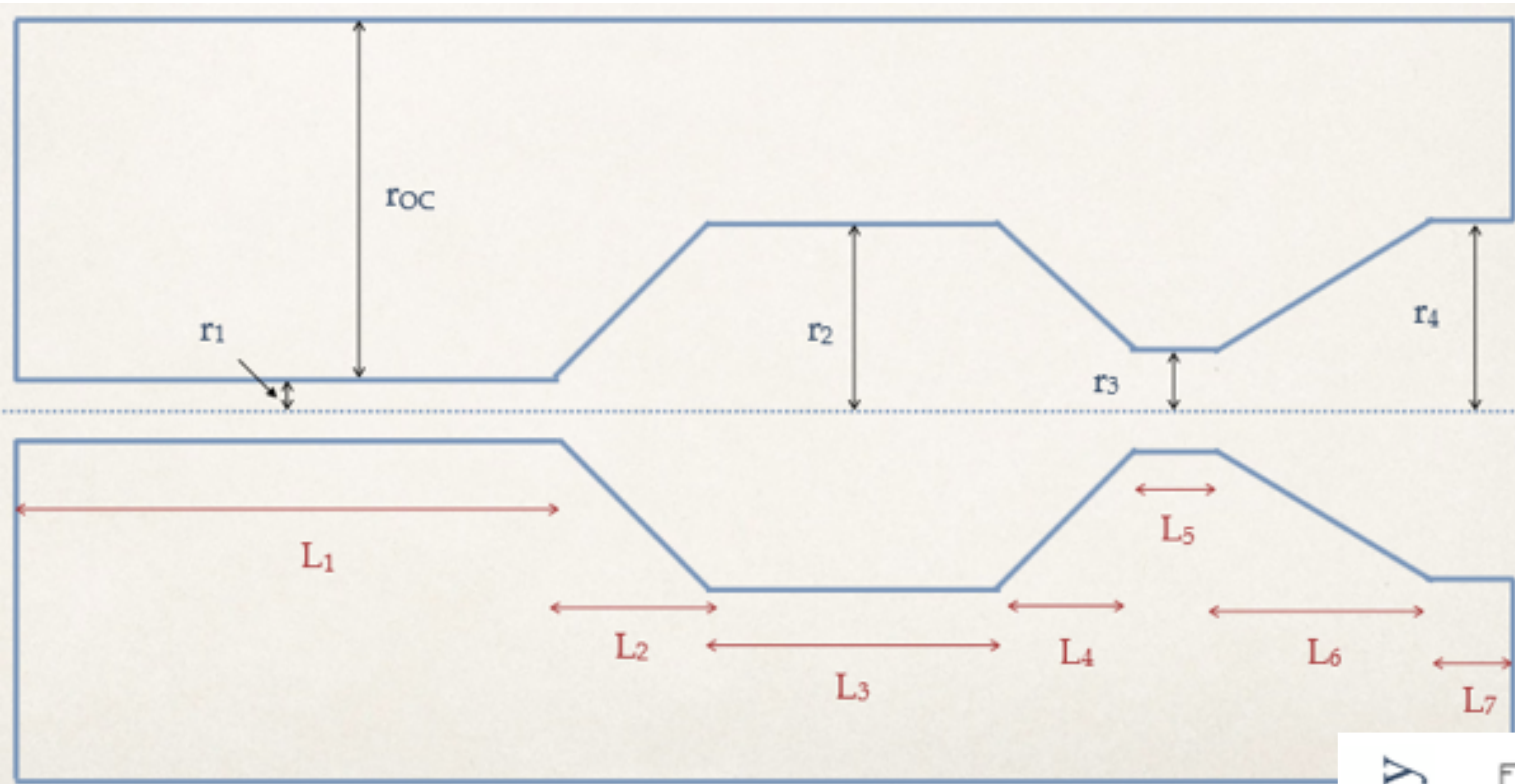
- $60 \leq E_{beam} \leq 120$ GeV
- Beam power 700 kW, upgradeable to 2.3 M
- Innovative design for safety and upgradeability.
- Many options still under development (decay pipe, horns, targets,etc)

Neutrino Beam Configuration



Challenge: Optimizing the focusing system for greater physics reach

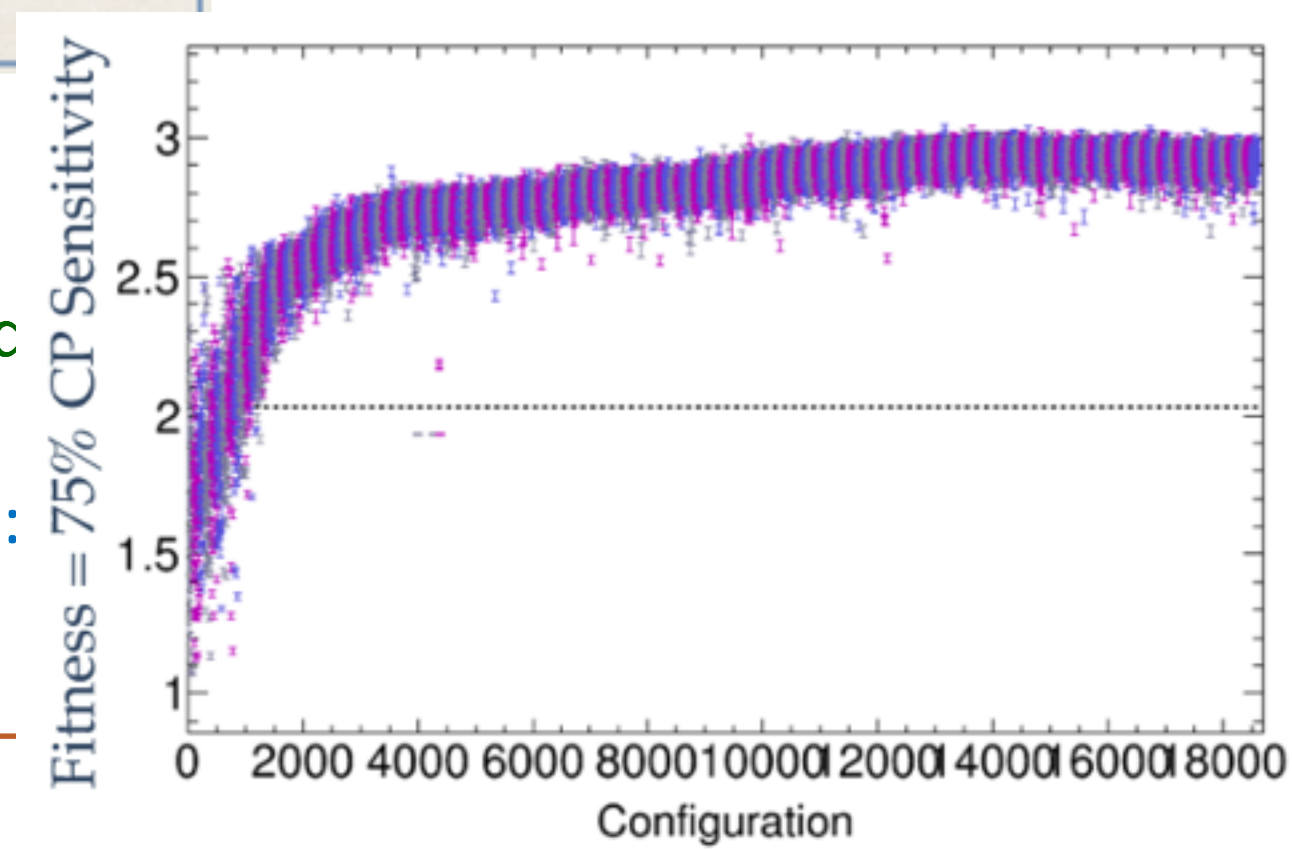
Genetic algorithm, inspired by work done by LBNO Collaboration
to optimize for CP Violation sensitivity



Genetic algorithm and new shape of Horn 1

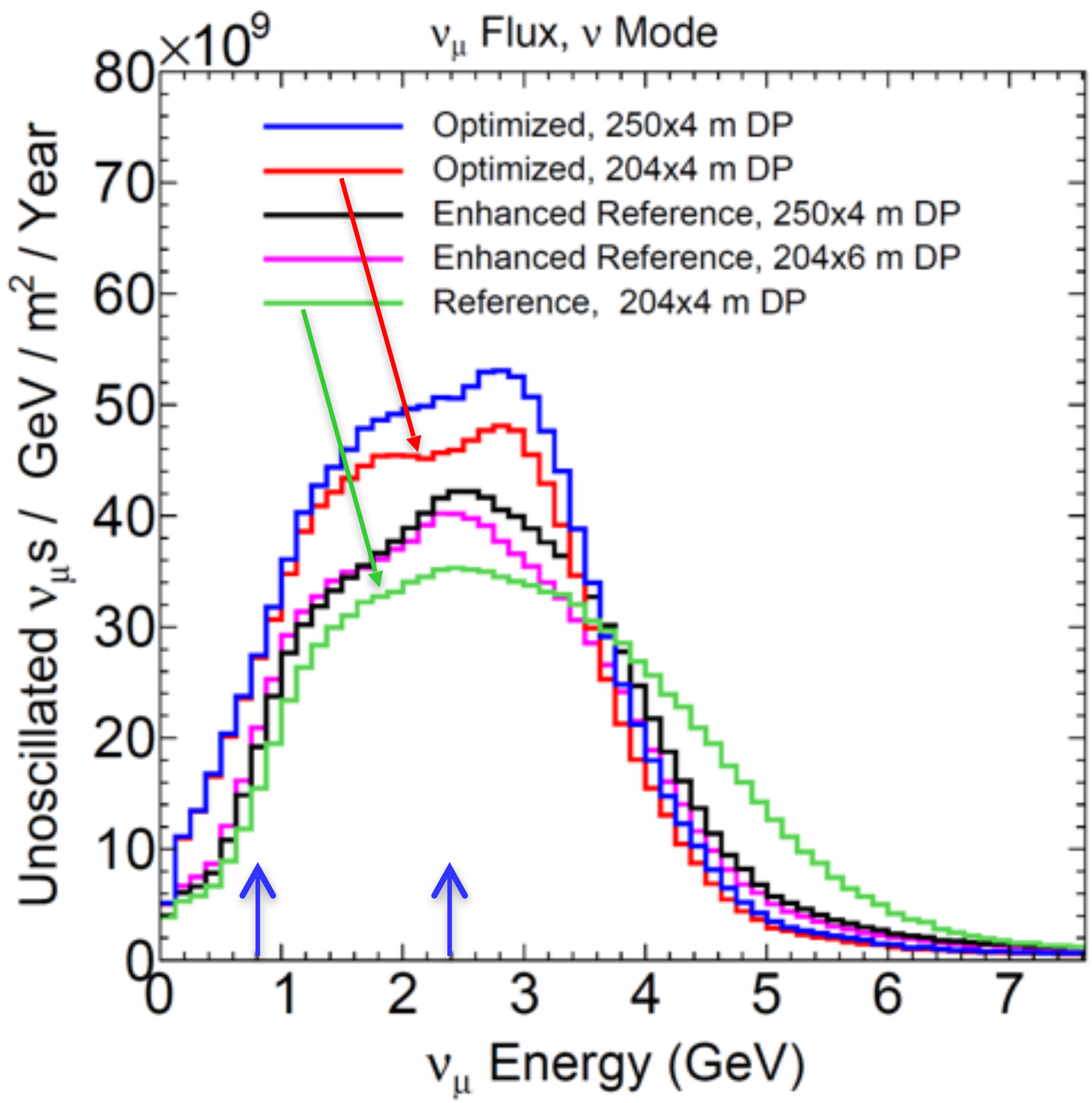
Horn 2 is NuMI shape in this case but rescaled radially and longitudinally

Target length varied – longer target preferred: $2 \rightarrow 5\ \lambda_I$



Neutrino Flux of best configurations compared with Reference Design

80 GeV protons



2nd *1st osc max*

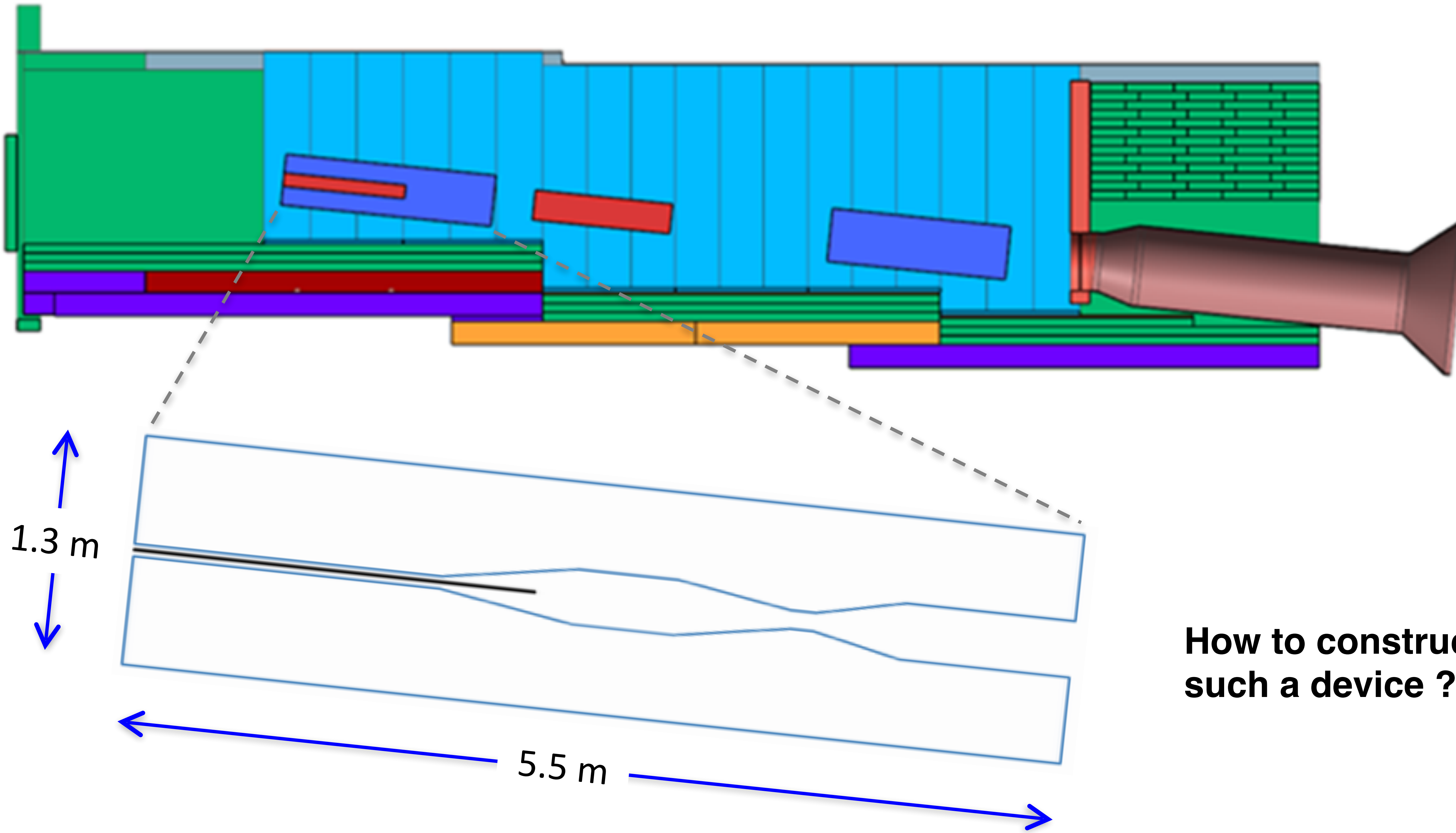
Substantial flux increase, especially at the 2nd oscillation maximum which is very important for the CP violation and mass ordering measurements.

… Optimization is continuing.

The optimization could have large consequences on absorber design as well as near detector.

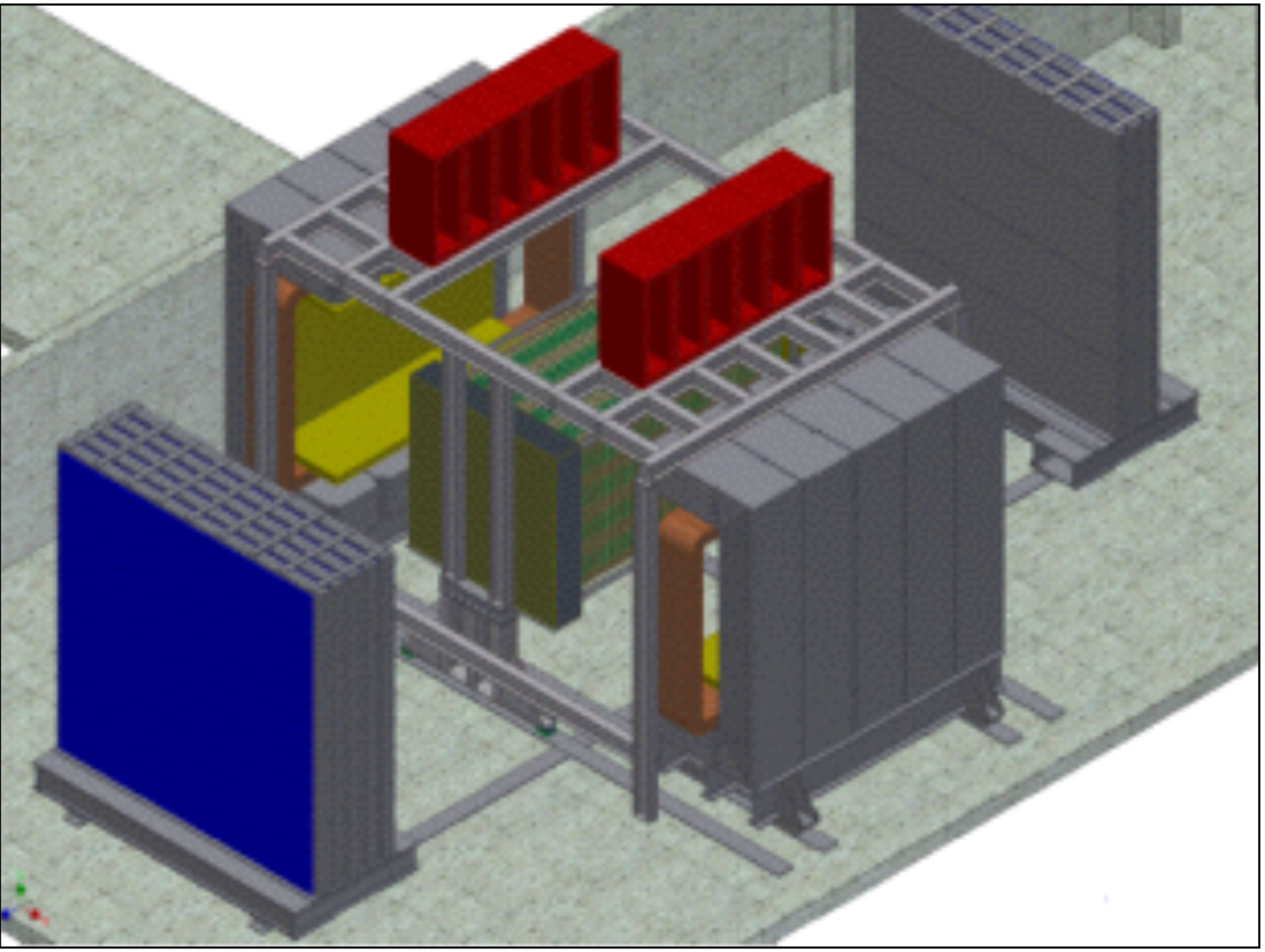
Target chase and optimized focusing systems

Reference Design Target Chase indicating the positions of the reference design horns (in red) and the optimized horns (in blue)



How to construct such a device ?

LBNF/DUNE Near Detector



- **Fine-Grained Tracker – 574 m from target**
  - **Low-mass straw-tube tracker with pressurized gaseous argon target**
  - **Relative/absolute flux measurements**
  - **High precision neutrino interaction studies $\approx 10^7$ interactions/year!**
  - **Additional target materials possible**

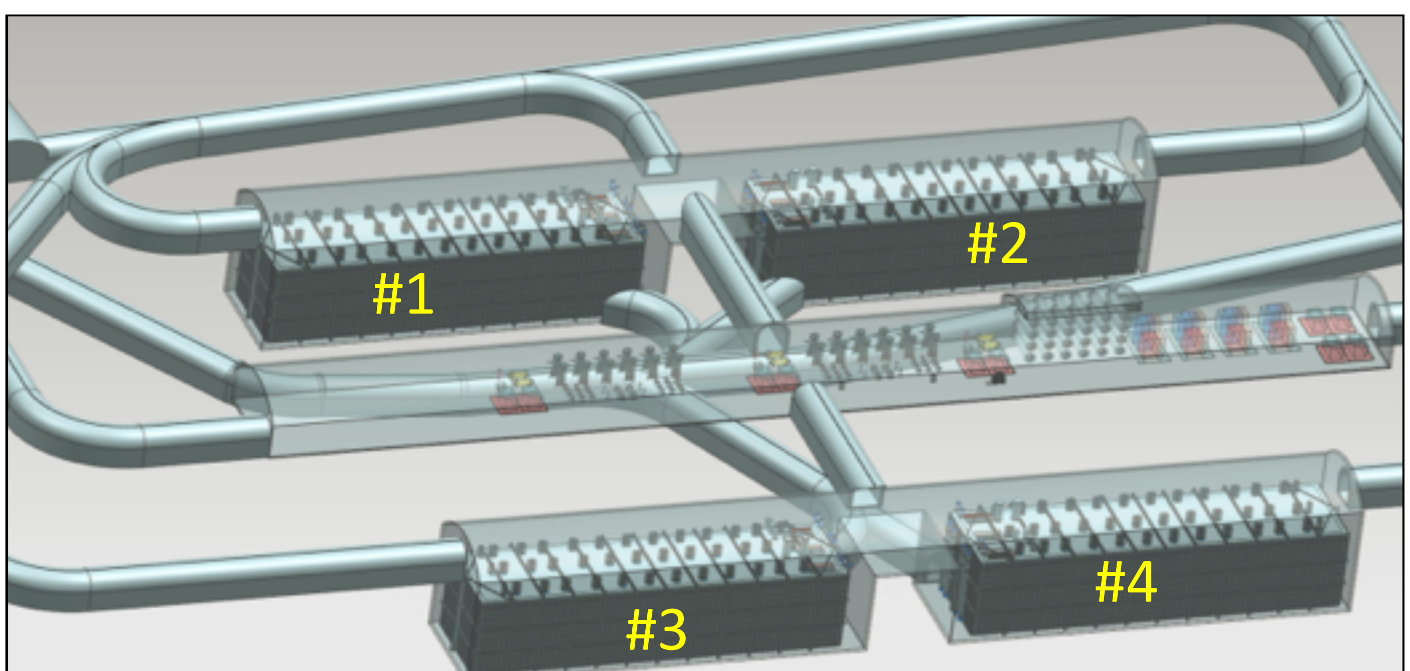
A liquid argon TPC or pressurized gas TPC are possible choices also.

The physics strategy and design of the ND is critical for LBNF. Simulations, reconstruction and R&D work is in initial phase with input from Indian colleagues. Open working meeting at FNAL on July 28-29.

Staged Approach to 40 kt

Four-Cavern Layout at the Sanford Underground Research Facility (SURF) at the 4850 foot Level (4300 m.w.e.)

- **4 caverns hosting four independent 10-kt (fiducial mass) Far Detector modules**
  - Allows for staged construction of the Far Detector
  - Gives flexibility for evolution of LArTPC technology design
    - Assume four identical cryostats: 15.1 (W) x 14.0 (H) x 62 (L) m^3
    - Assume the four 10-kt modules will be similar but **not identical**



Far Detector at Sanford Underground Research Facility in the Black Hills of South Dakota

SURF site is open for science with all legal issues in order

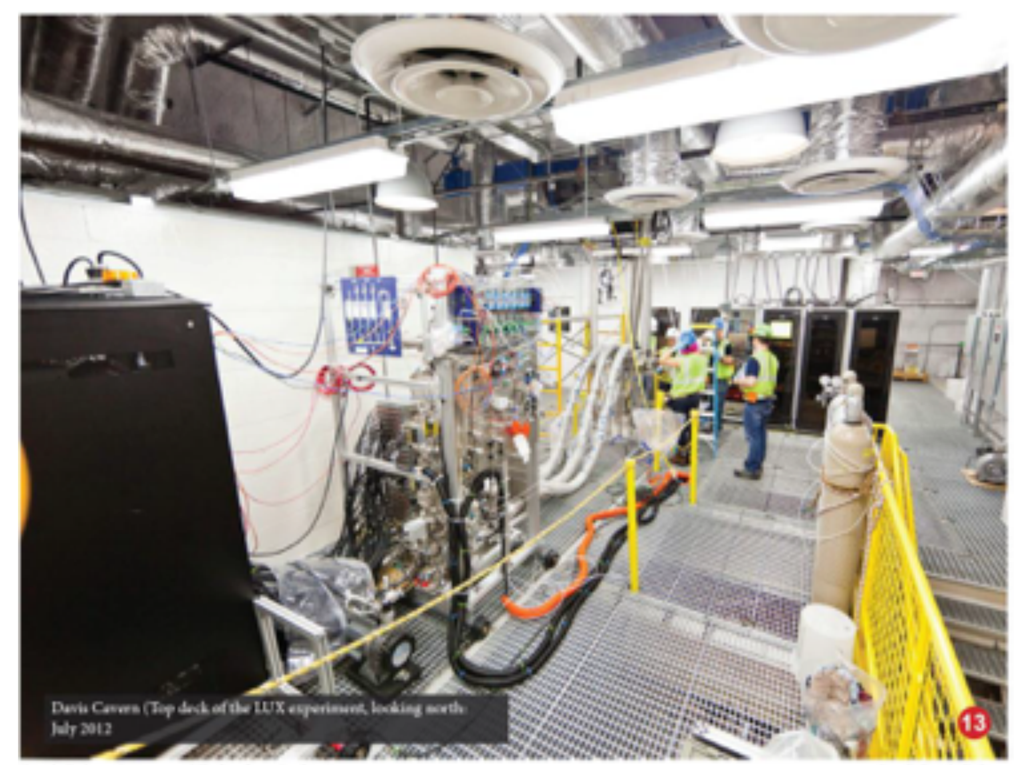
Donated to Science

The shafts go down to 4850 ft and are being upgraded. We have benefited greatly from early interactions with LNGS.

Sanford Underground Research Facility
(Greatly benefitted from LBL leadership !)

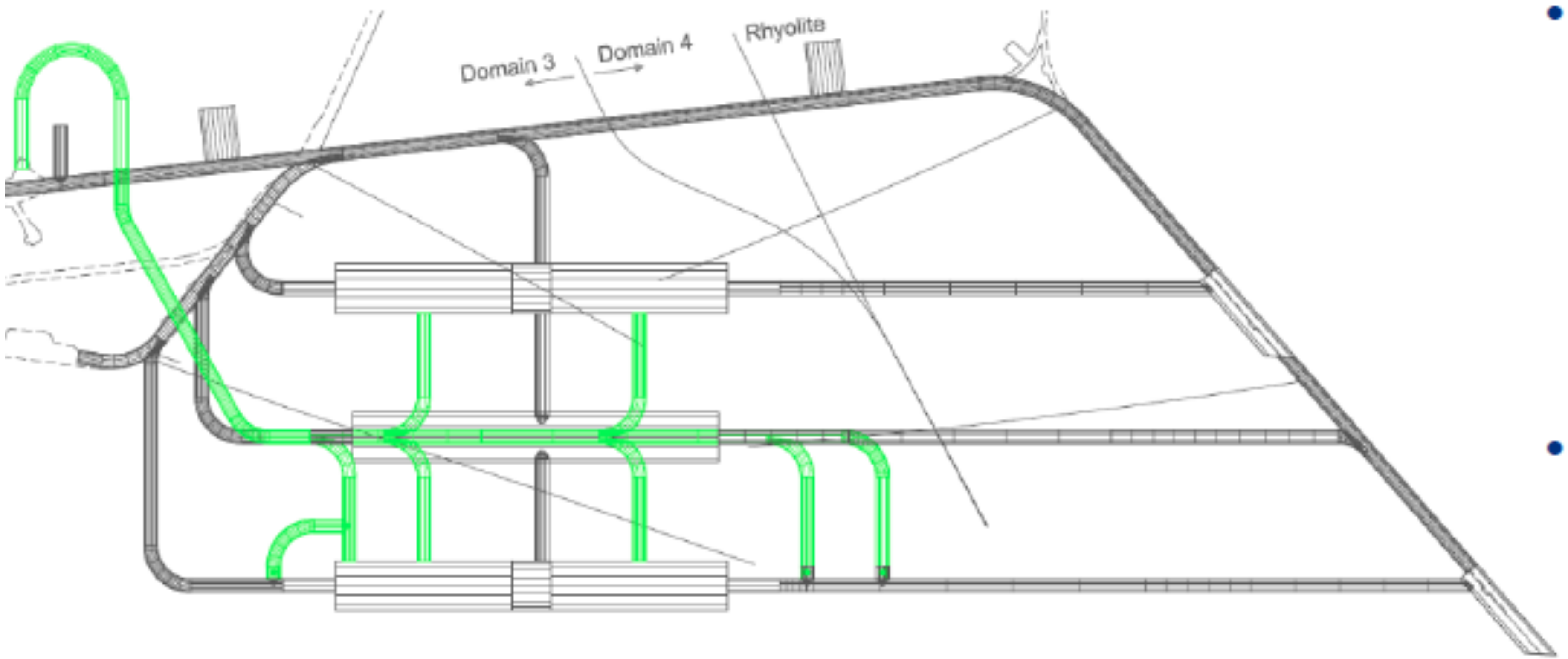
Majorana (0νββ)

- Experimental Facility at 4300 MWE
- Two vertical access shafts for safety.
- Shaft refurbishment has been on-going and has reached 1700’ level
- Total investment in underground infrastructure is >$100M.
- Facility donated to the State for science in perpetuity.

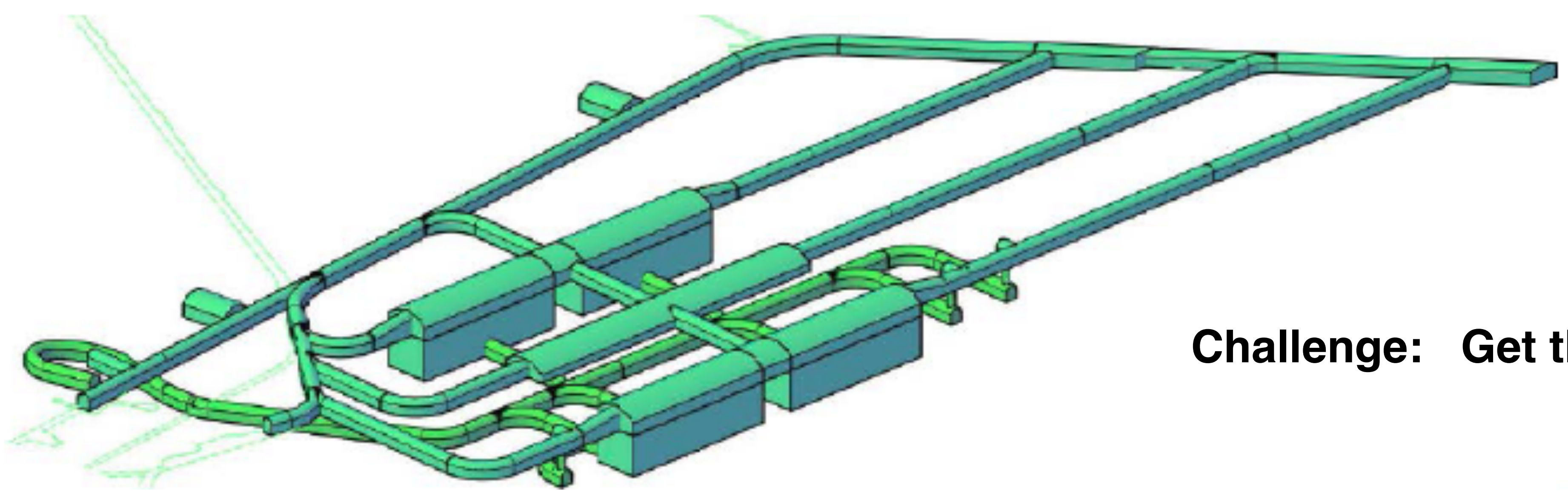


LUX (dark matter)

Cavern configuration for LBNF

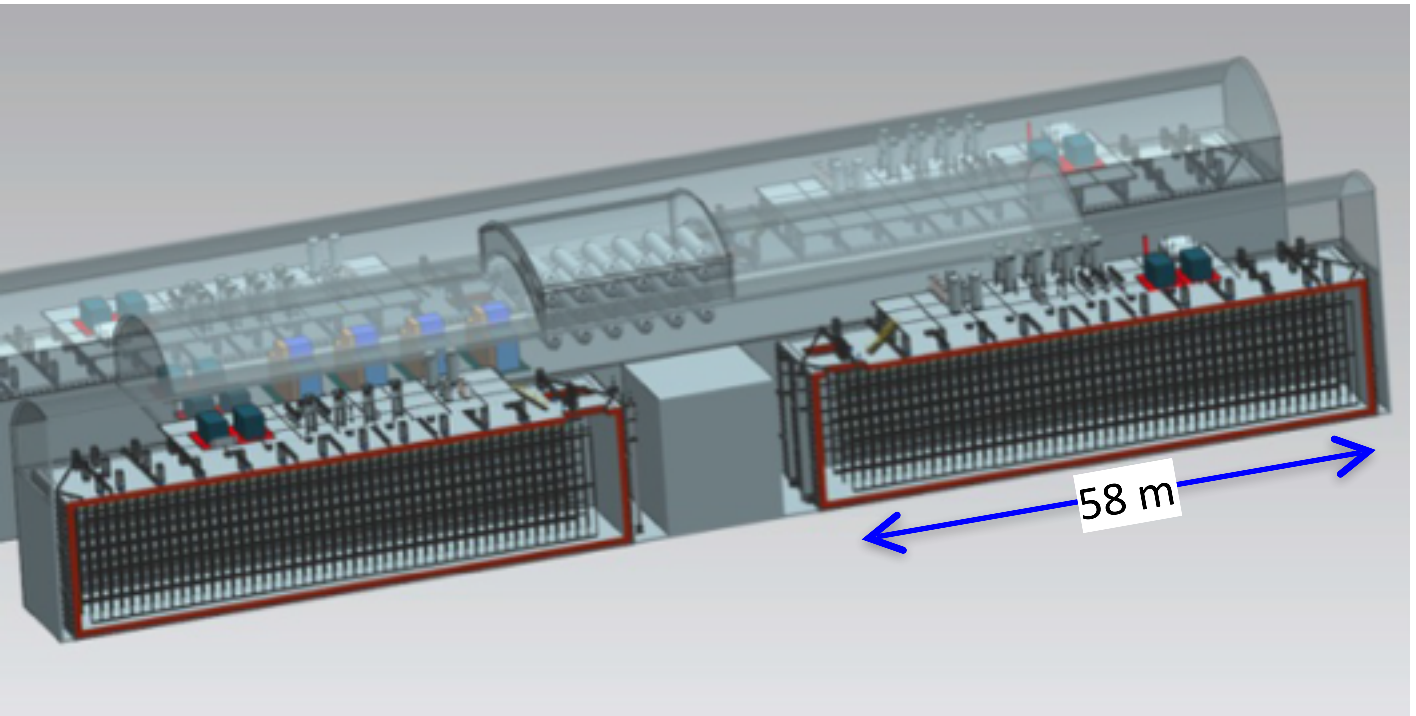


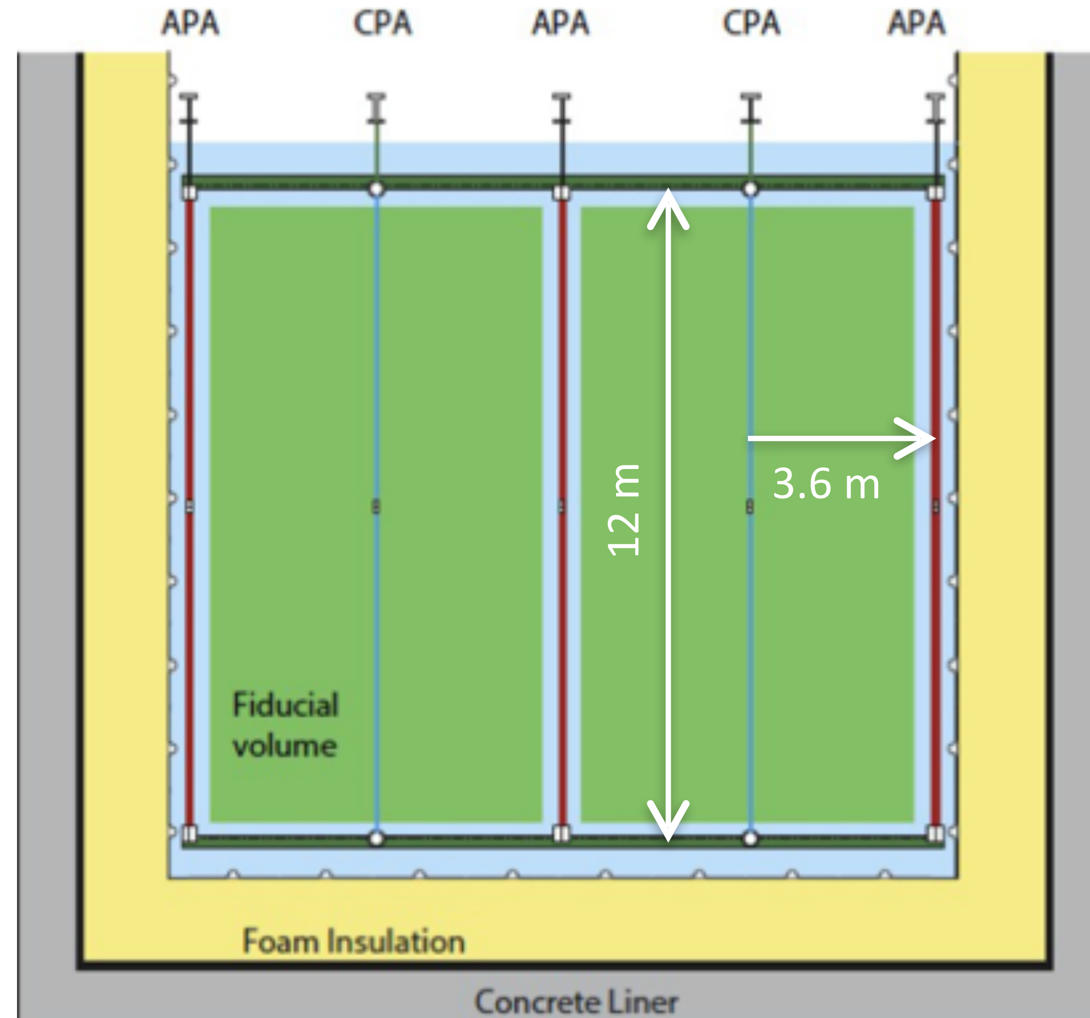
- Two parallel caverns each have two 10 kt detector pits with a laydown space in between
- The CF utilities and cryogenics are in a separate parallel chamber, thus no conflict with cryostat & detector laydown

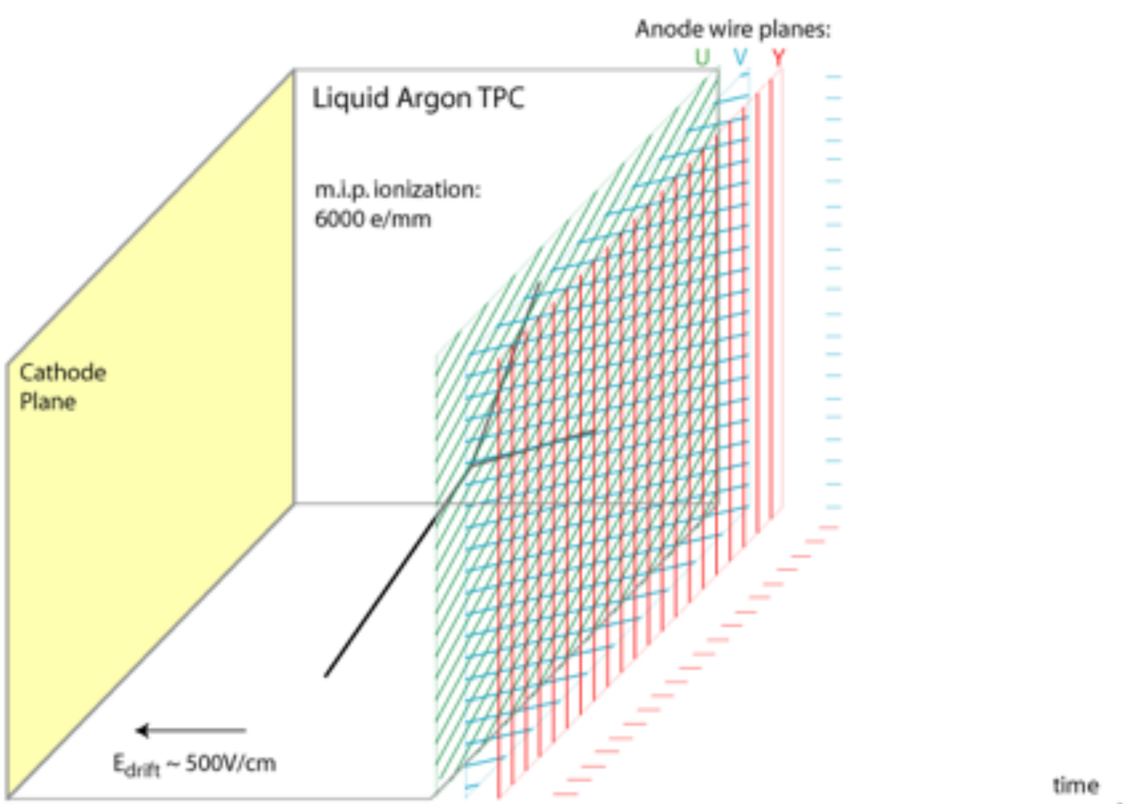


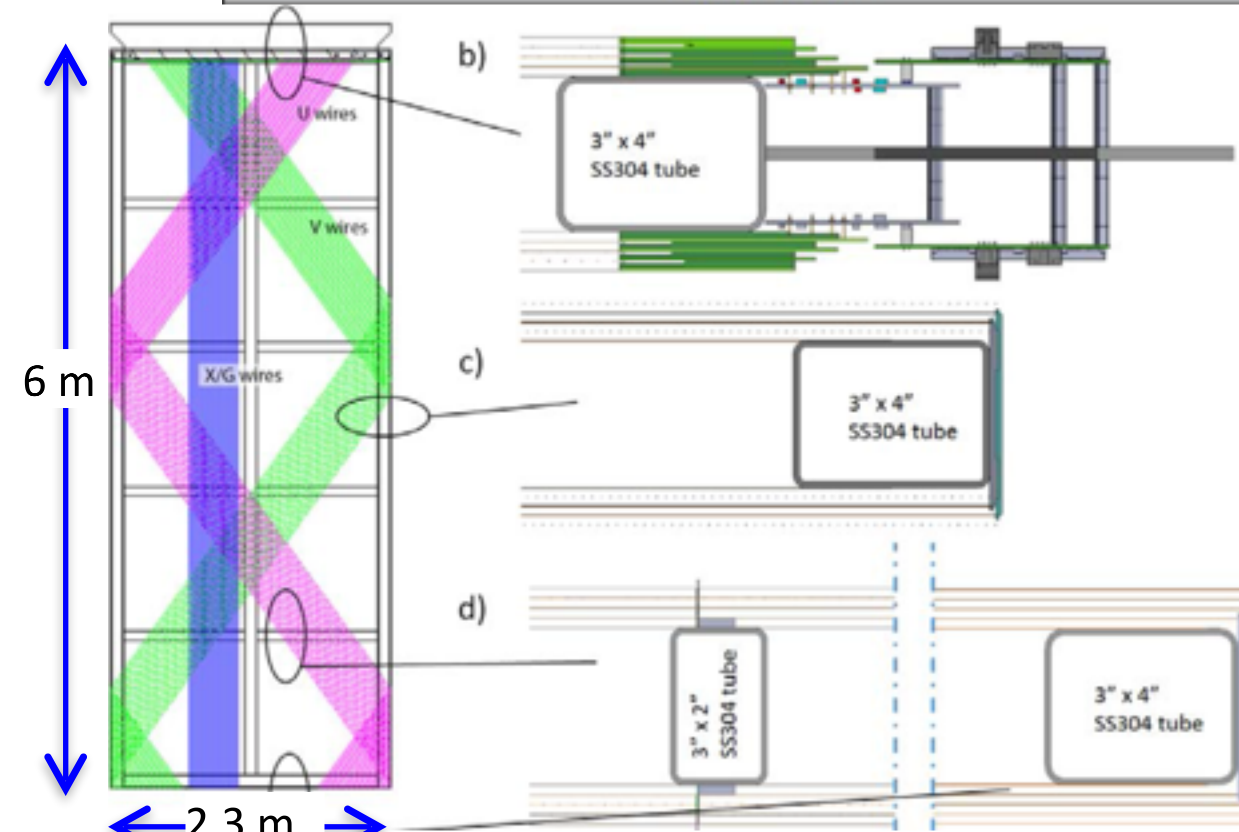
Challenge: Get this constructed rapidly !

Reference Design: Single-Phase LAr TPC





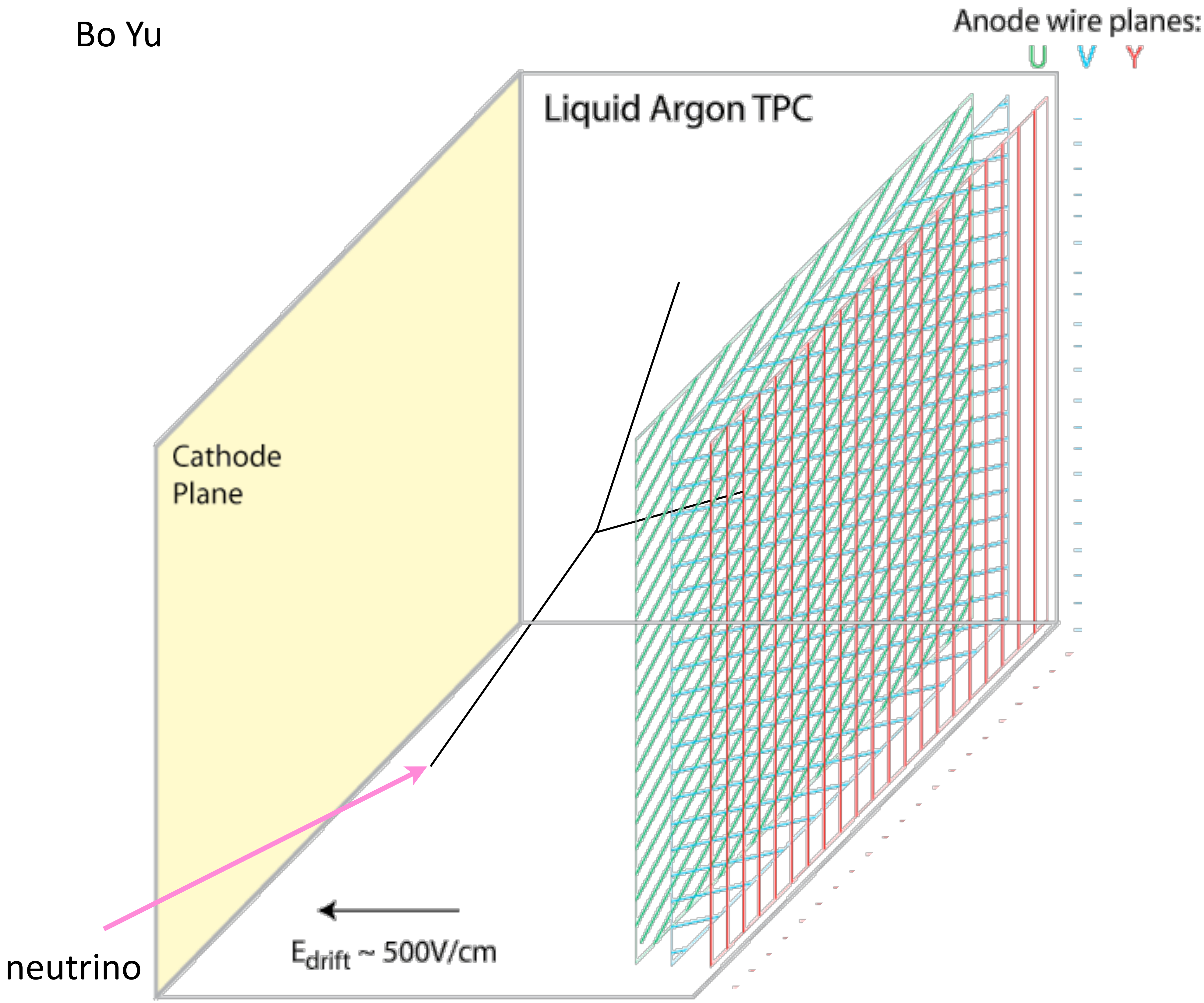




Anode Plane Assembly (APA)

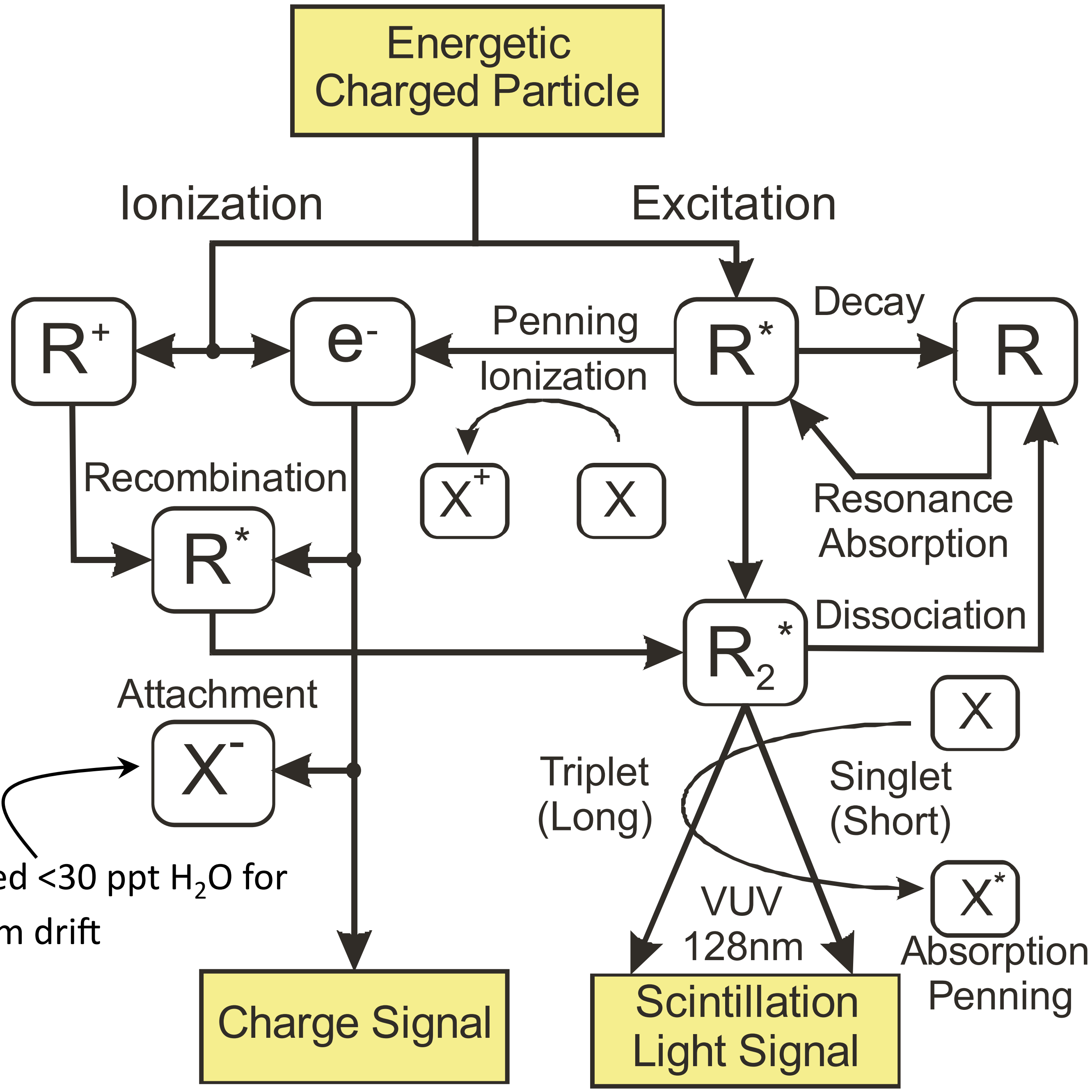
How Does a LArTPC Work?

Bo Yu



LAr also scintillates. We intend to detect the light also.

What happens to the energy as a charged particle traverses in LAr?



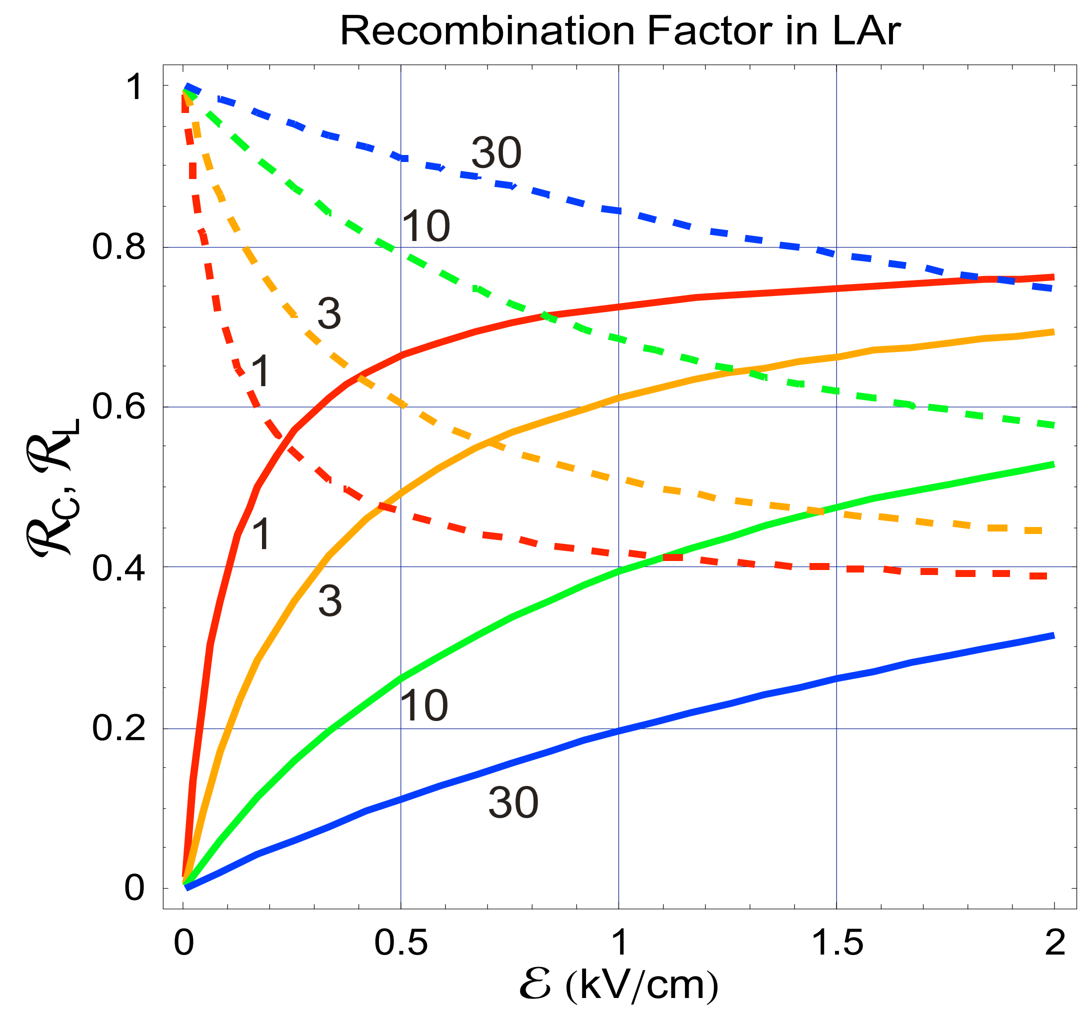
Need <30 ppt H_2O for 2.5m drift

E→∞
42,000 e/MeV
8980 e/mm for MIP

E→0
51,300 ph/MeV
10,900 ph/mm for MIP

(40,000 for NaI(Tl))

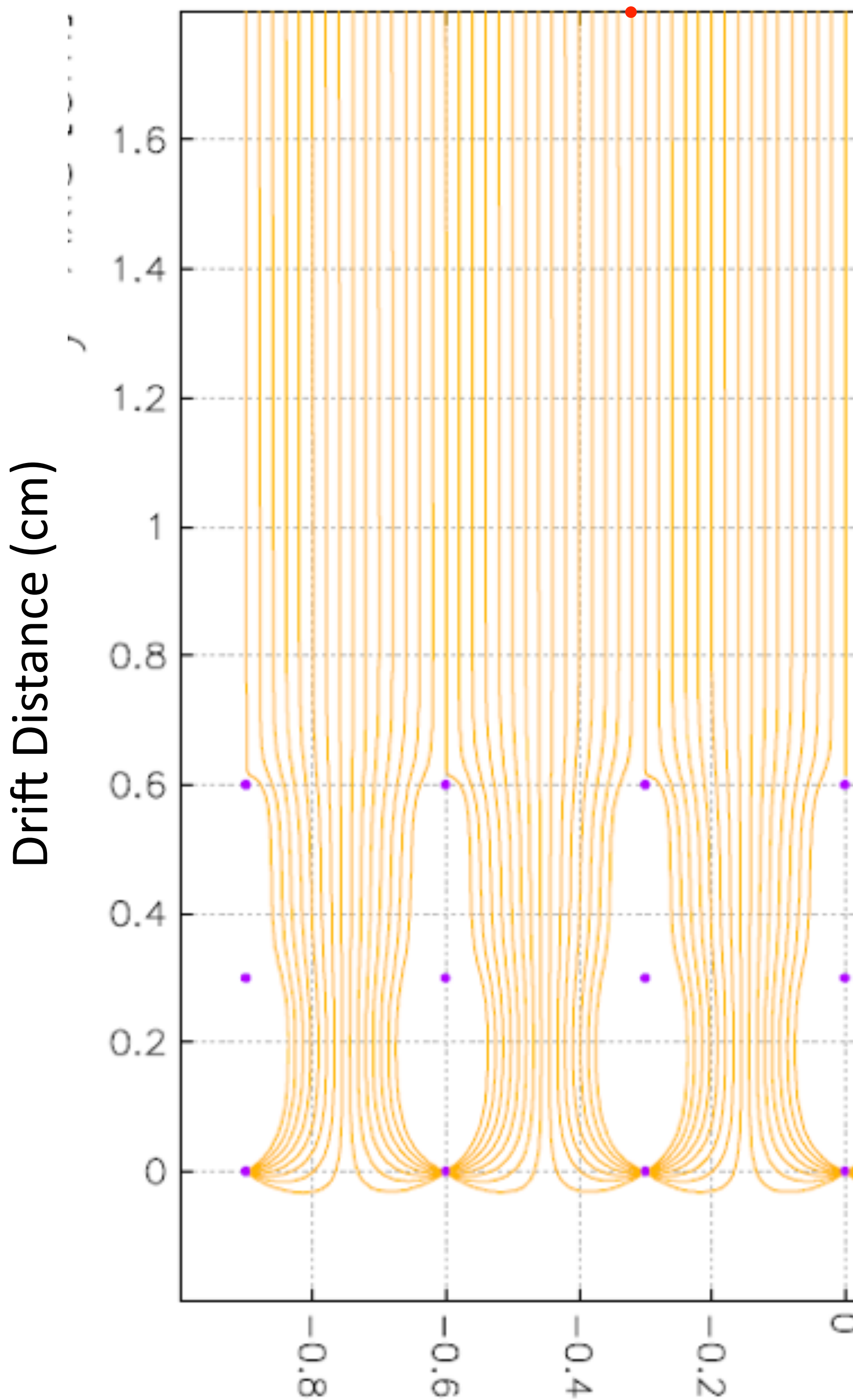
R={LNe, LAr, LKr, LXe}
X={N_2, O_2, H_2O, ...}

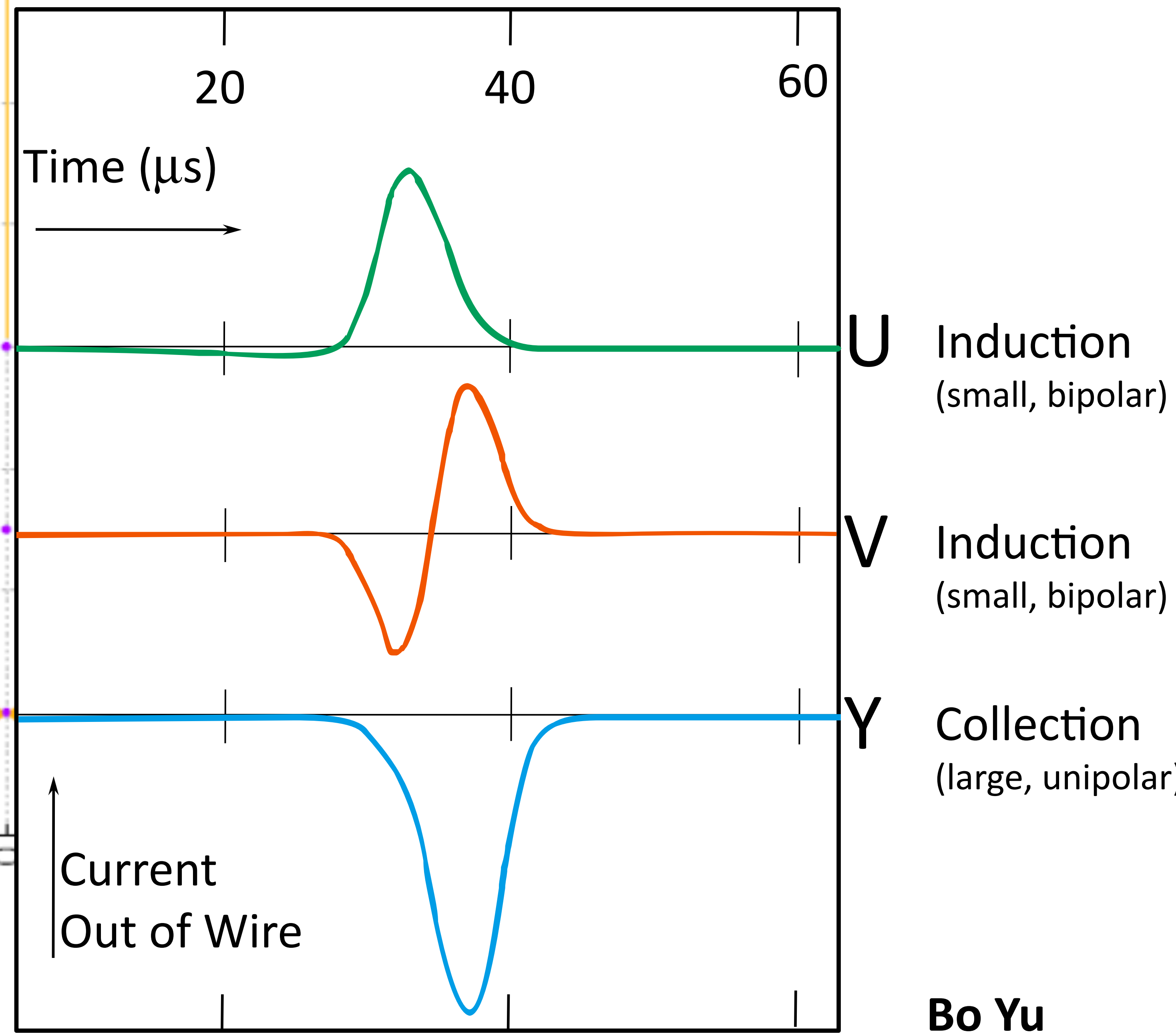


Ratio w/r/t full yield
Solid: charge, Dashed: light
Numbers: Specific Eloss in MIPs

Charge Signal Formation

Induction by
and
Collection of
electrons on wires



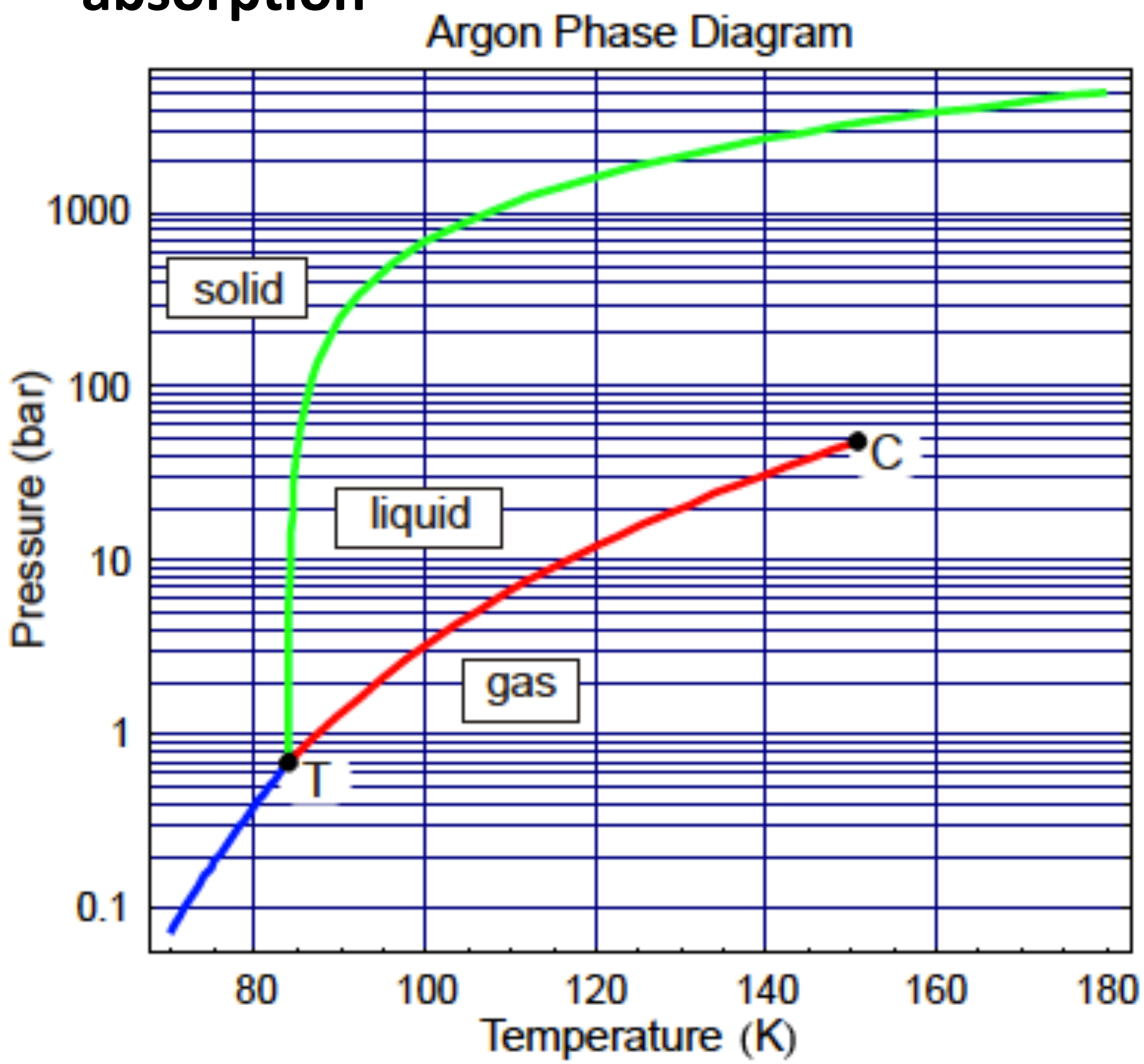


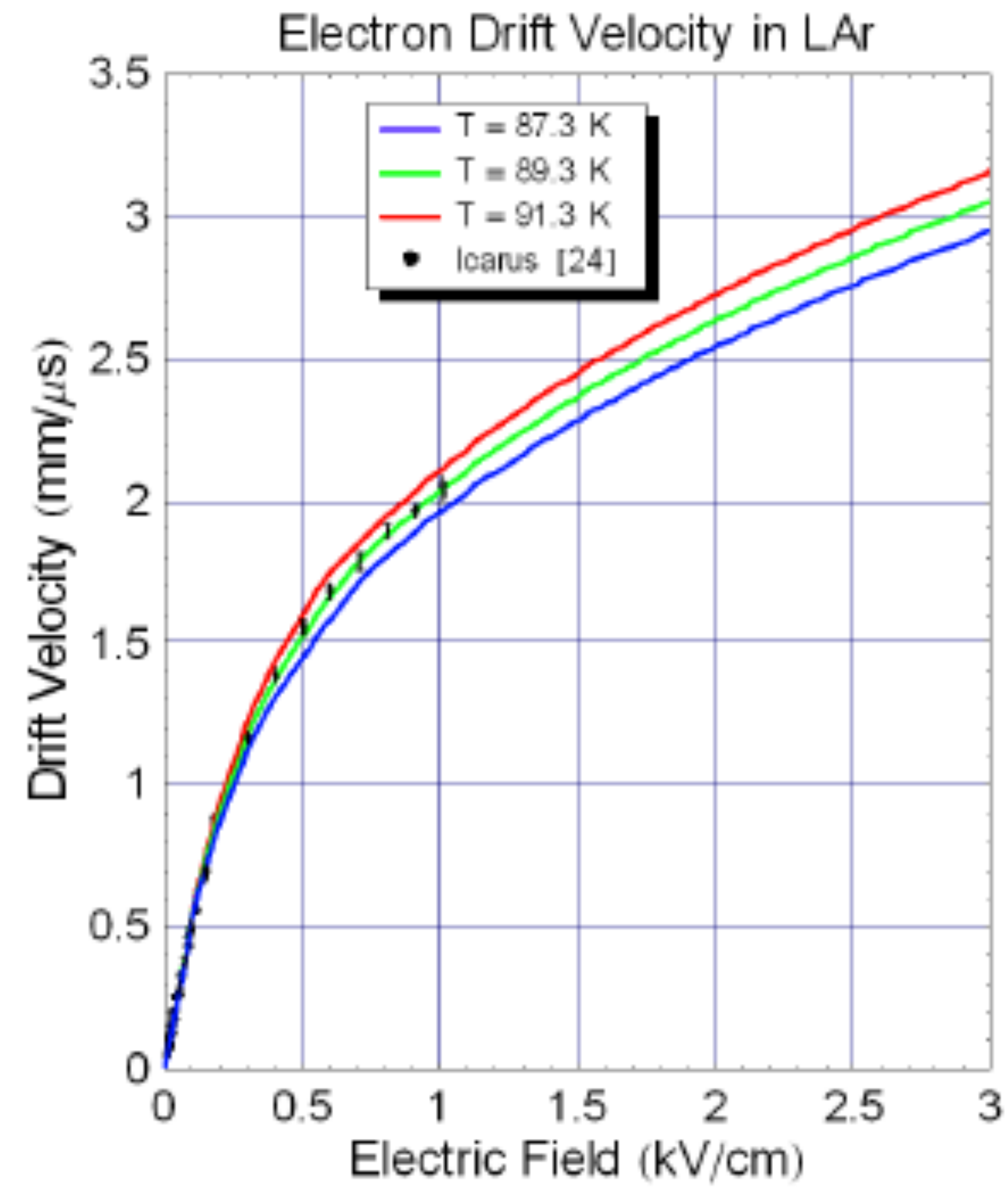
Signal formation starts upon motion of the charge.

Bo Yu (BNL)

Key Technical Issues for a Liquid Argon Detector

liquid argon must be extremely pure: ~1 part in 10^{10} to allow long drift without absorption





It is cold ! And this makes it inaccessible and difficult to work with.

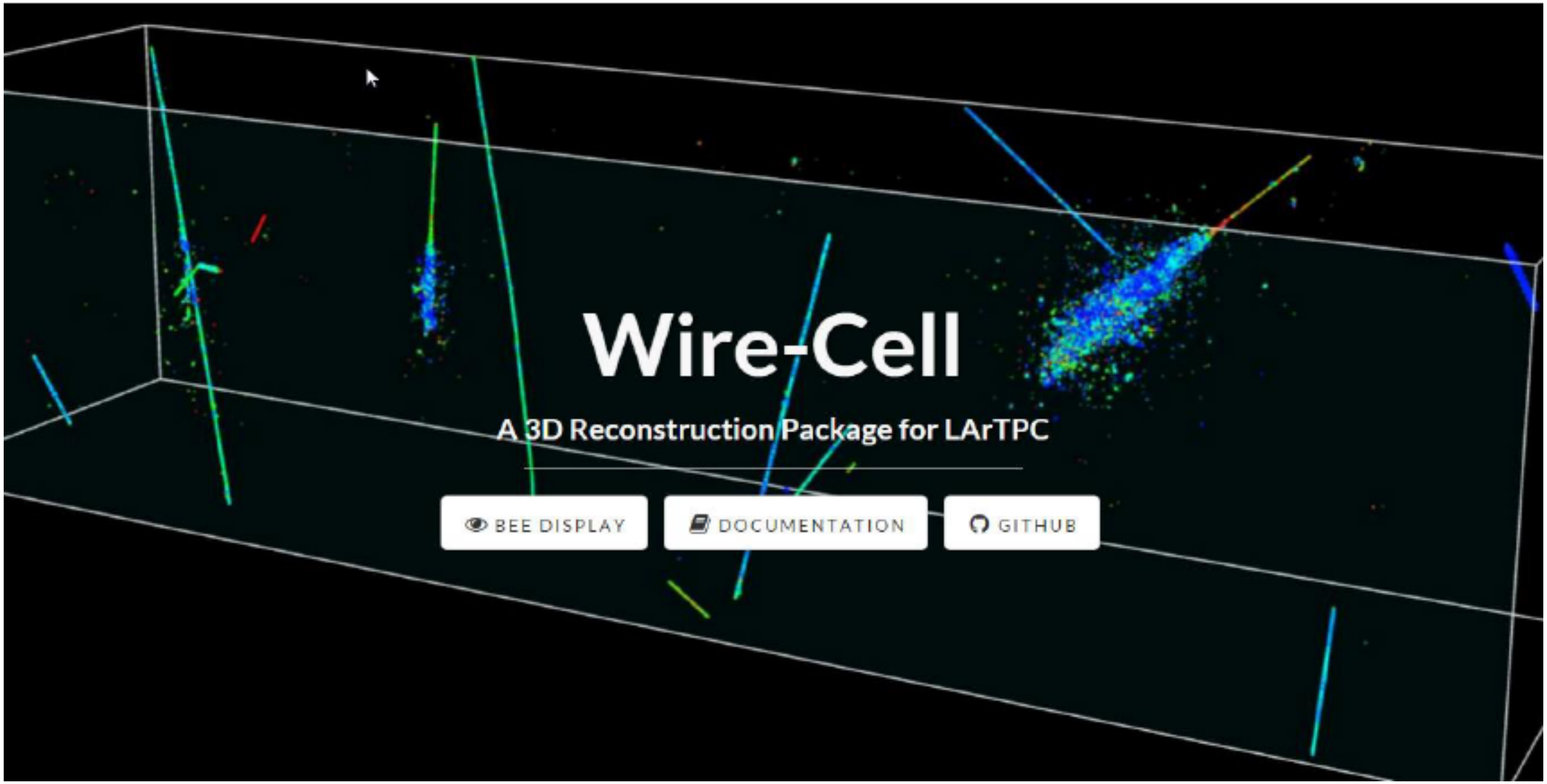
It is slow ! Electrons drift slowly. Drives many issues of design.

Challenges of liquid argon TPC

- LArTPC was chosen for high efficiency (>80%) for CC events, high EM resolution (15%/$\sqrt{E}$), Excellent particle ID.
- Cryogenic systems requirements, modeling, and verification.
- Light Detection: Current design uses TPB coated acrylic panels within the anode plane with SiPM readout. Requirement is time measurement for proton decay and supernova.
- Reconstruction of events with high efficiency: We have a new method for 3D reconstruction called Wire-cell that seems promising. Optimize for physics requirements.
- Cold electronics technology: how does one certify quality, and time to failure rates ?
- Prototyping (integration): protoDUNE at CERN.

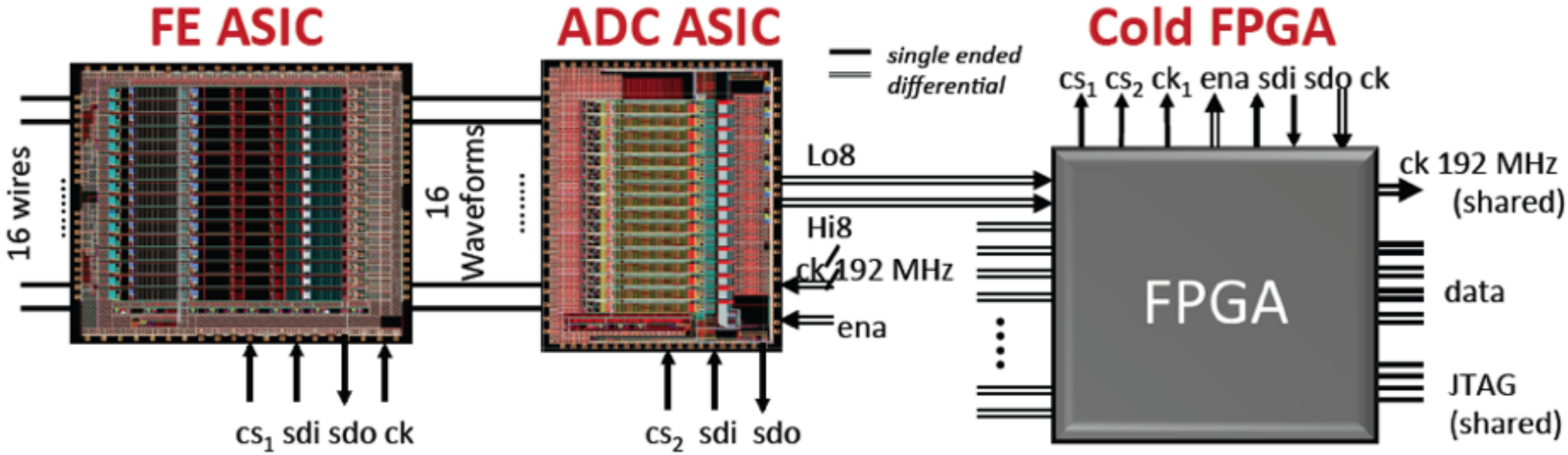
The Wire-Cell Homepage

http://www.phy.bnl.gov/wire-cell/



We are using ideas from tomographic reconstruction to produce 3D images from multiple time slices. Challenge: how to use time and charge information to minimize the ambiguities inherent in wire readout.

Cold CMOS Electronics



- low-noise analog amplification
- programmable gain, shaping, coupling

Production ready

- ADC 12-bit 2MS/s
- small buffer
- 2 x **8:1 multiplexing**

Prototype V4 in 1 mo

- **Digital Control Development**
- **Result for 35t defines baseline configuraiton**

Cold Digital Control Development

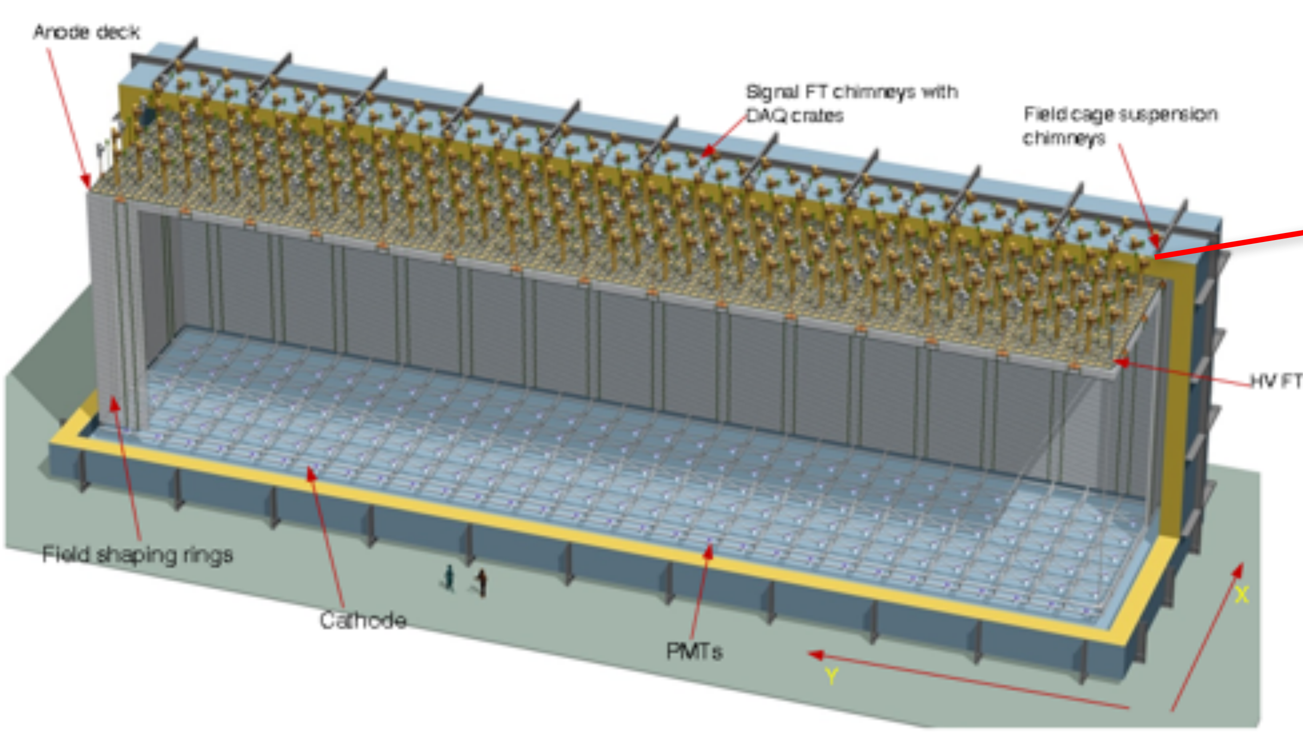
Decide Cold commercial FPGA or Custom ASIC in FY15
Functionality defied in 35t test
Prototyping design rules for cold digital process now.

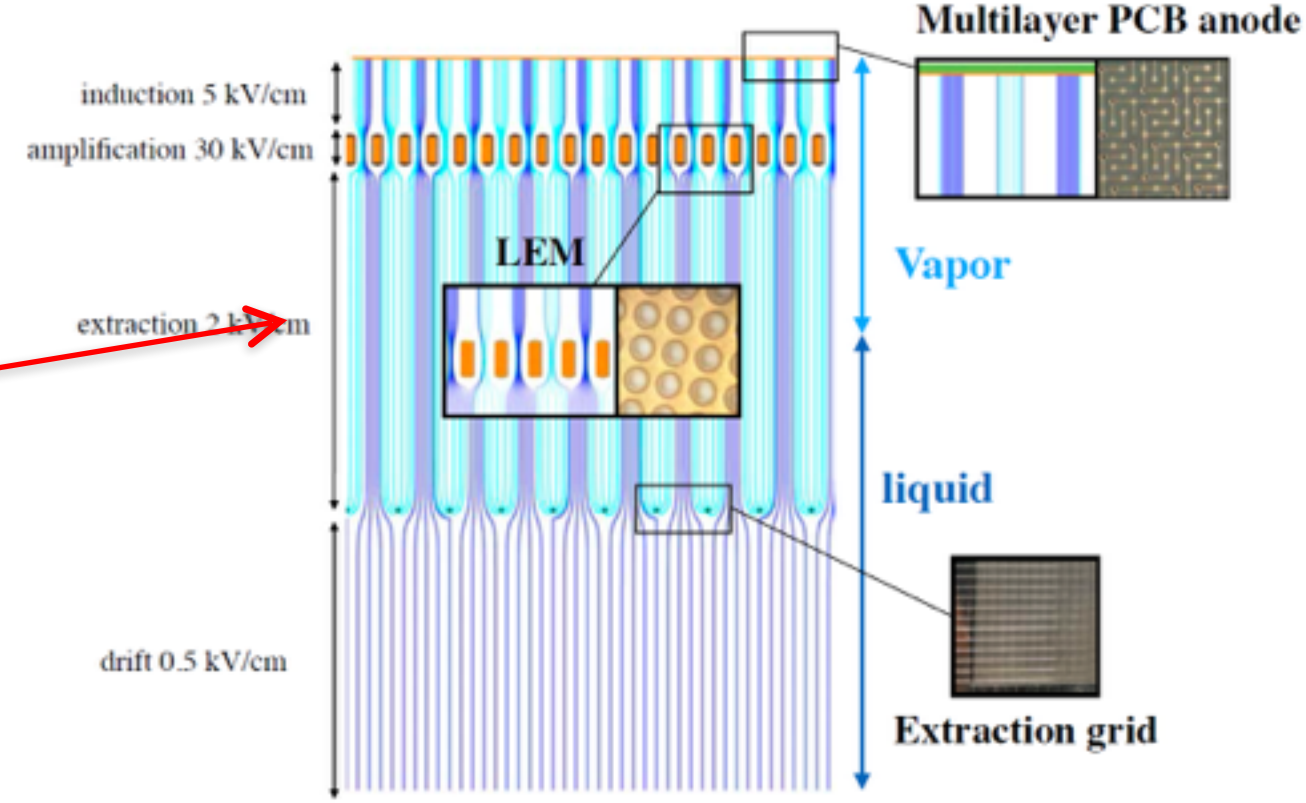
QA is a very big issue and will require large well integrated collaboration of institutions.

Many issues here
Architecture
Low level testing
Power management
Decision tree
Risk analysis
(30year lifetime)
Interfaces and
redesign of ADC.

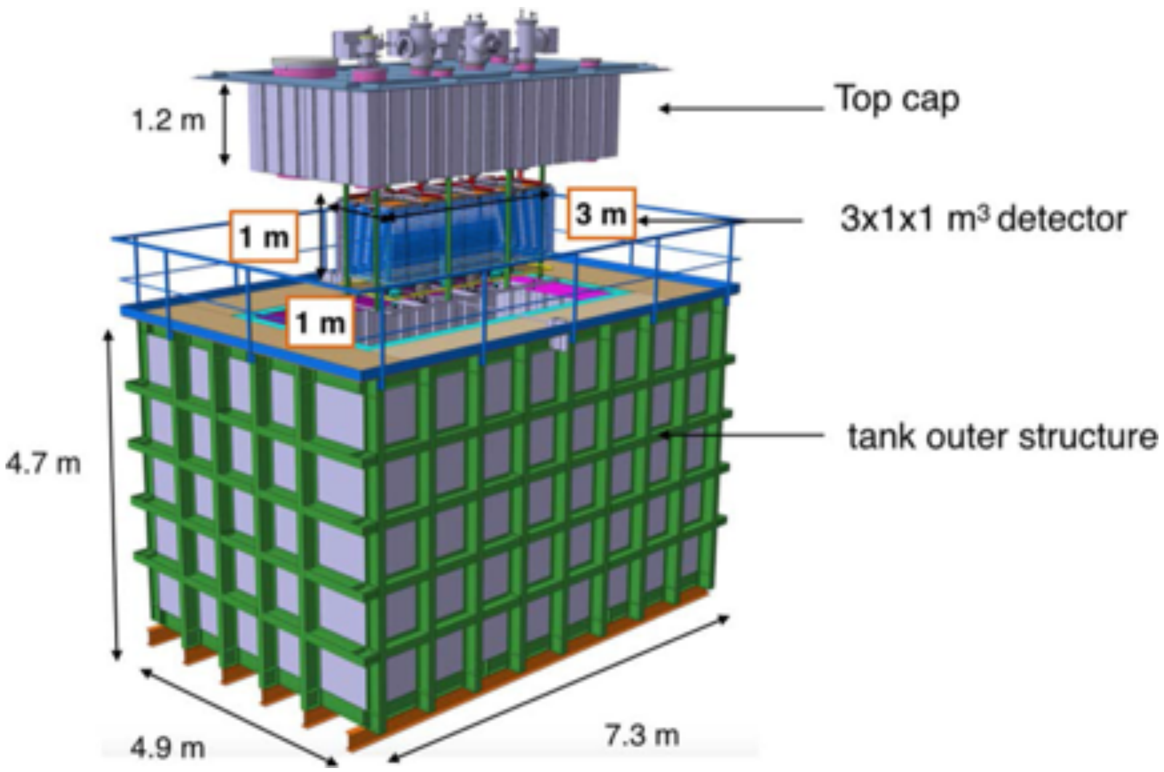
DUNE collaboration recognizes the potential of the dual-phase technology

- Strongly supports the WA105 development program at the CERN neutrino platform
- If demonstrated, could form basis of second or subsequent 10-kt far detector modules

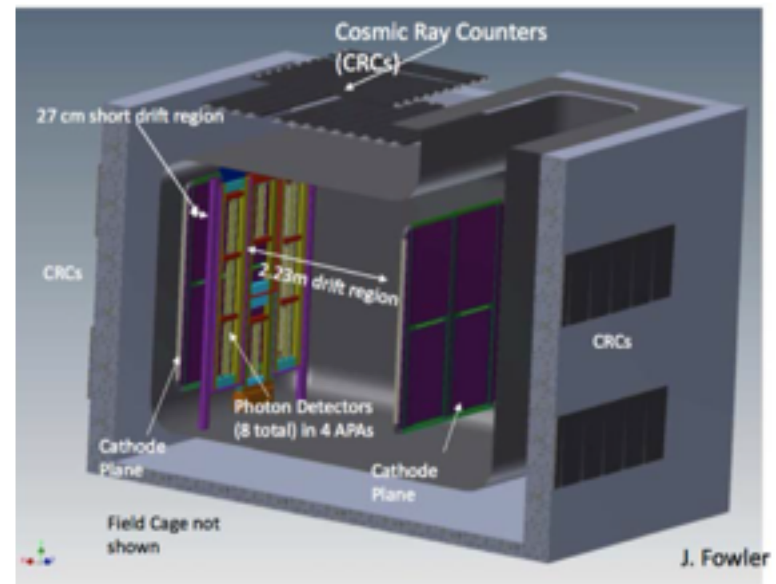




Far Detector Prototypes



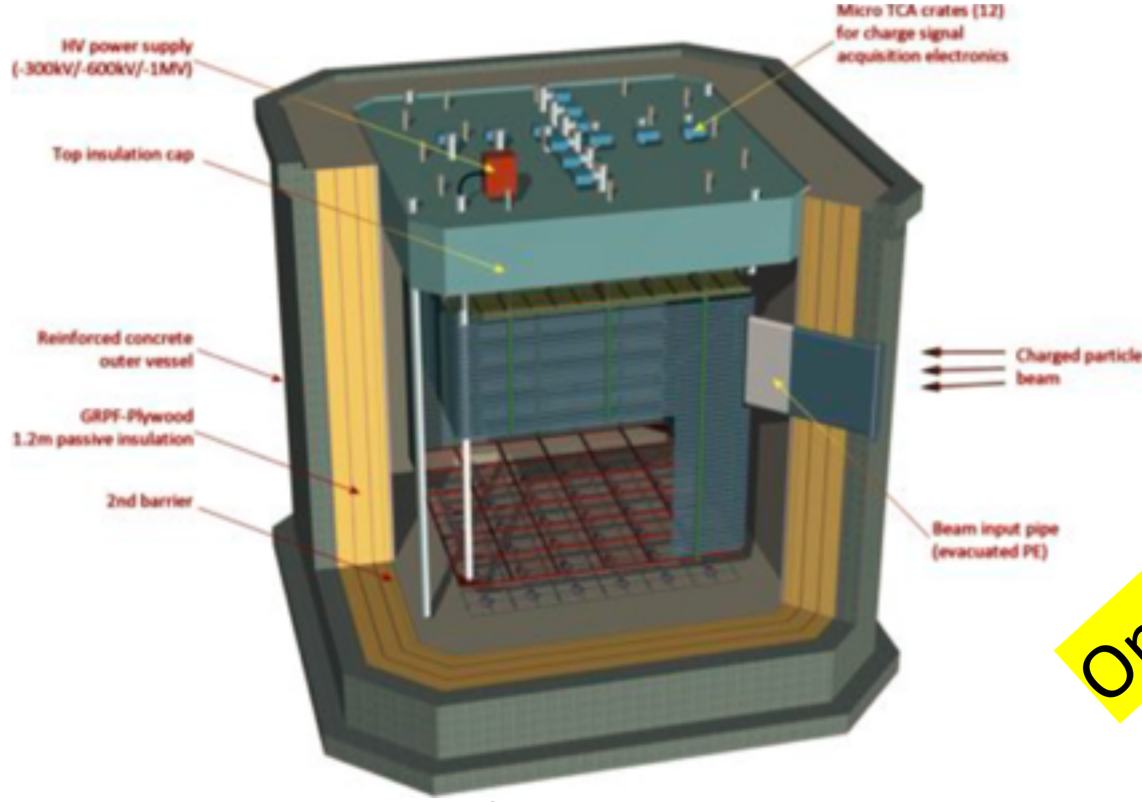
1 x 1 x 3 m^3 dual-phase prototype at CERN



35 t single-phase Prototype at Fermilab

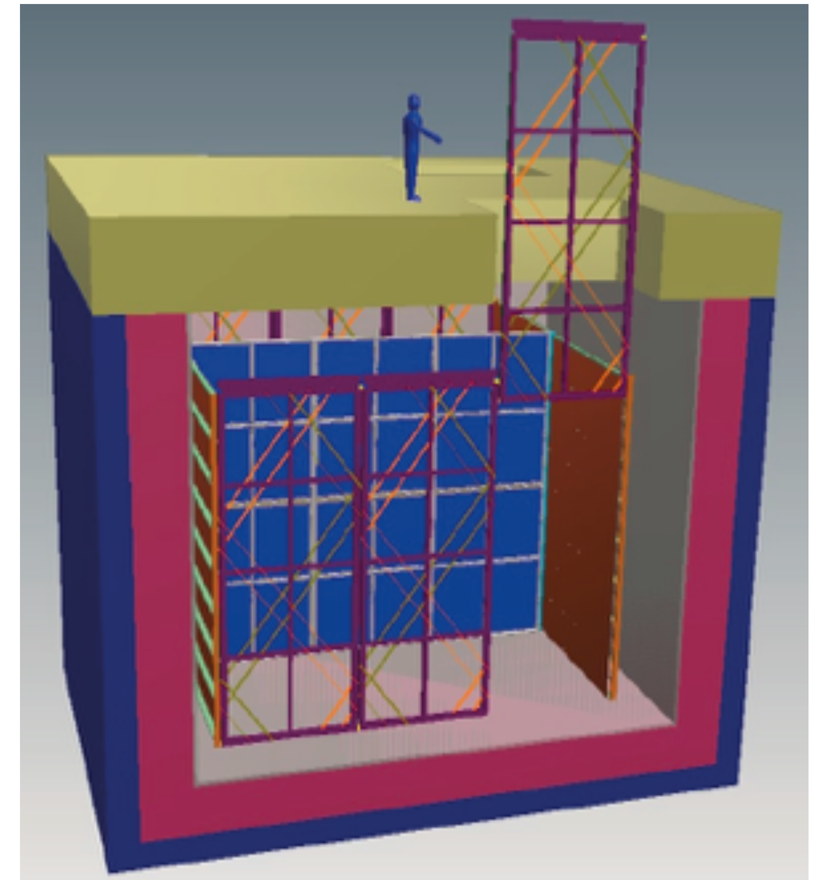
Under construction now

Far Detector Prototypes

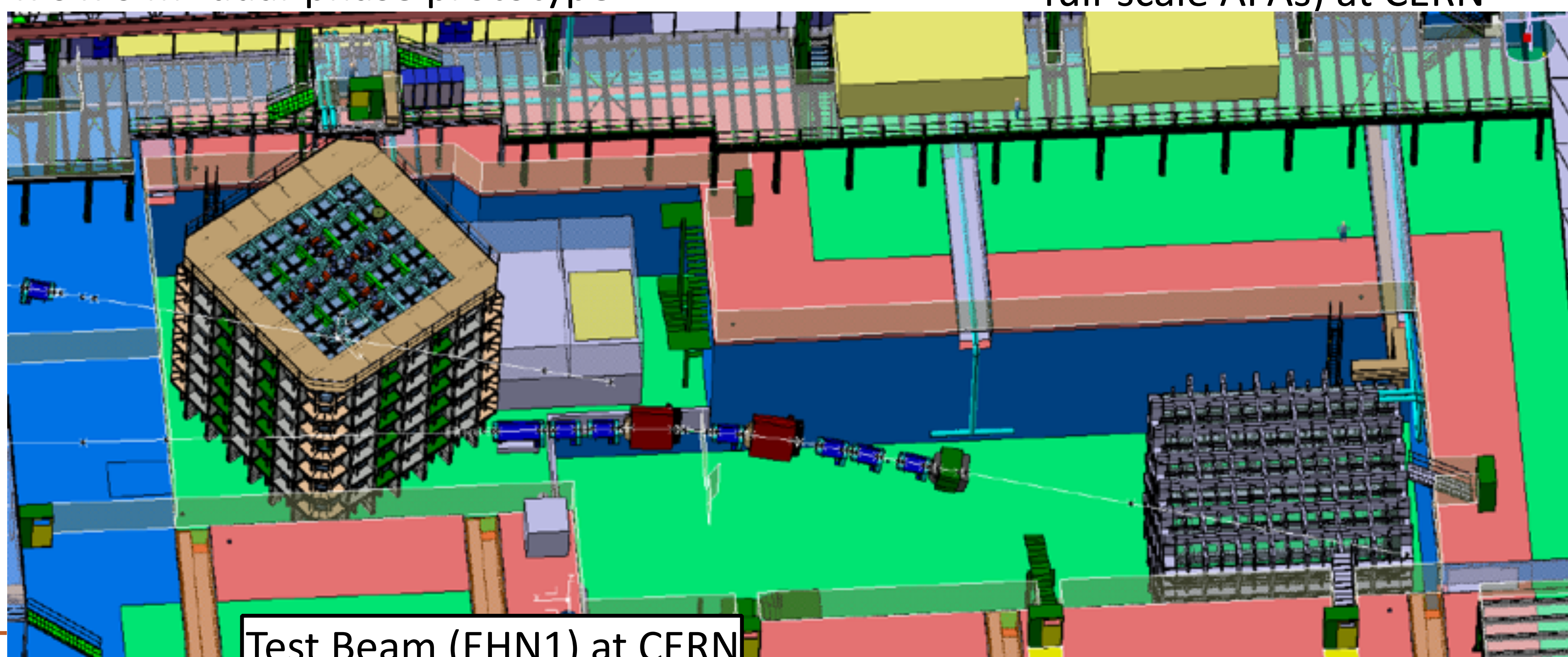


WA105: 6 x 6 x 6 m^3 dual-phase prototype at CERN

Operational by 2018

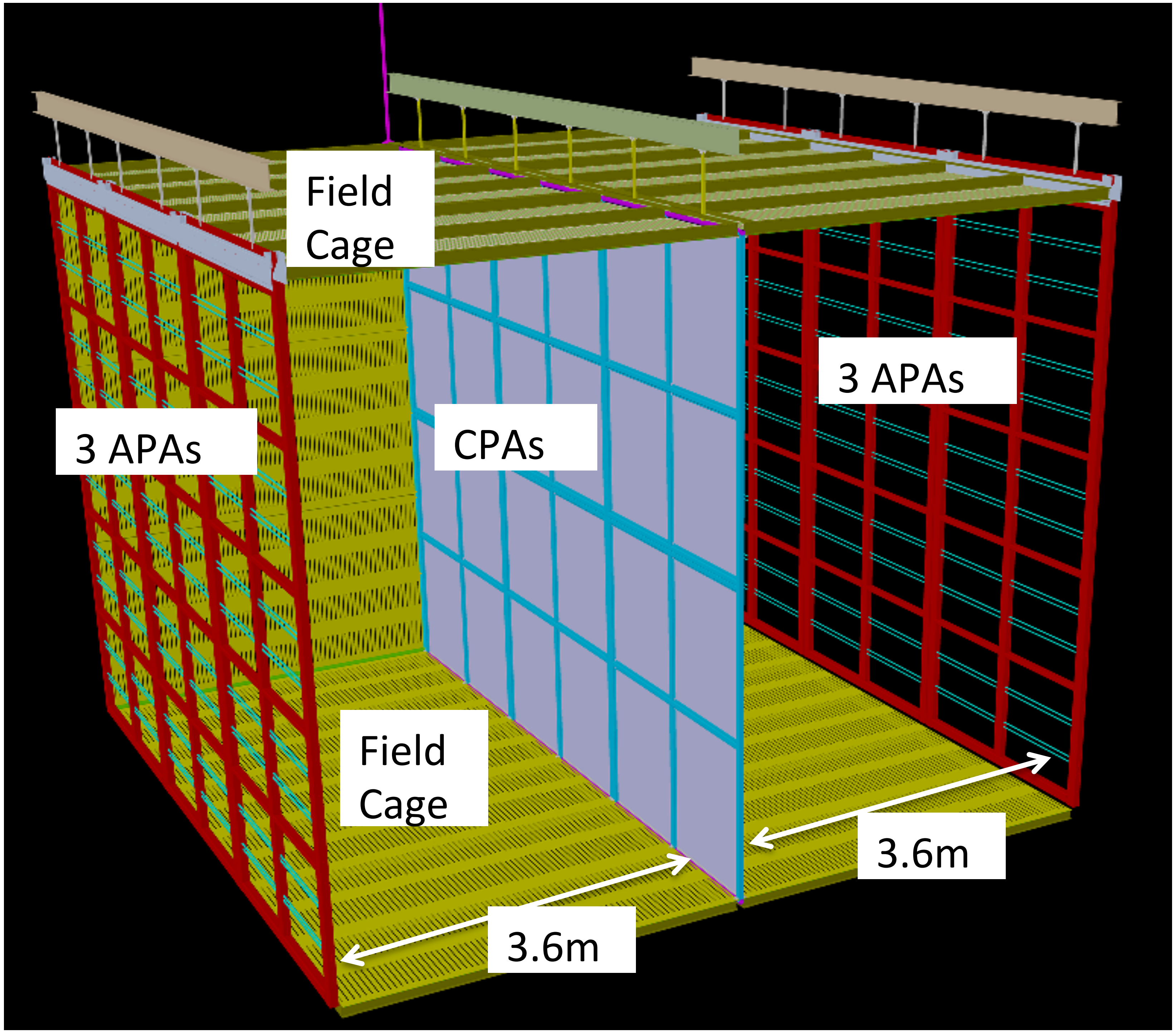


protoDUNE: single-phase prototype (6 full-scale APAs) at CERN



Test Beam (EHN1) at CERN

A View of protoDUNE TPC



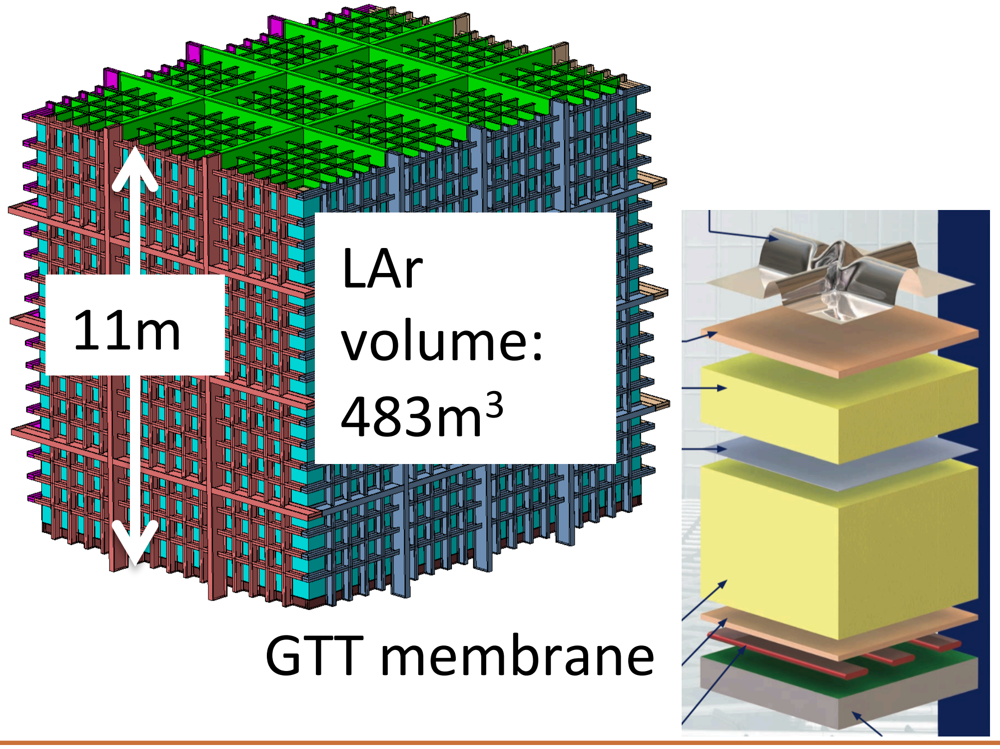
Detector components are same as for DUNE far detector

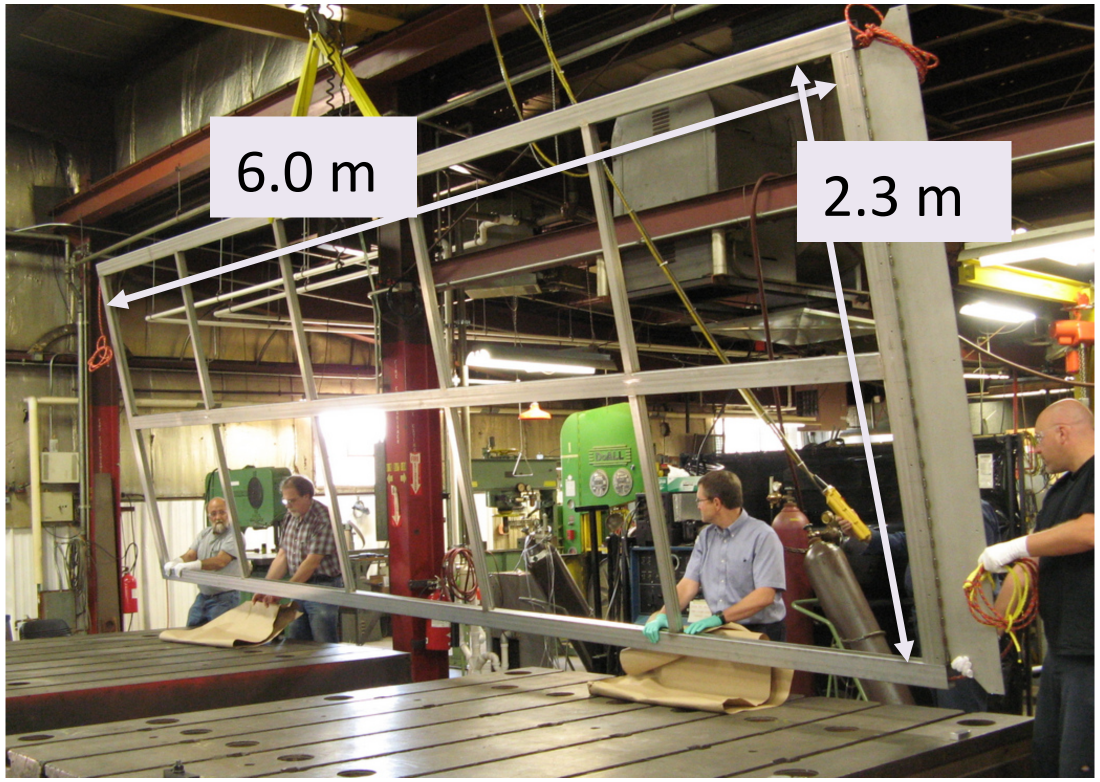
Keep option to reduce drift distance to 2.5m (reduced space charge effects)
→Use experience from 35t detector to inform strategy

ProtoDUNE Parameters

- 700t (400t) total (active) LAr mass
- 6 full size APA design as for first DUNE 10 kt module
  - TPC: 15360 readout wires
  - PDS: 60 photon detector panels (2.1×0.1 m^2), 240 PDS readout channels
- 6 cathode plane assemblies

Internal: **7.8 m (Transv) x 8.9 m (Parallel) x 8.1 m (Height)**
External: **10.6m (Transv) x 11.7 m (Parallel) x 11.0 m (Height).**

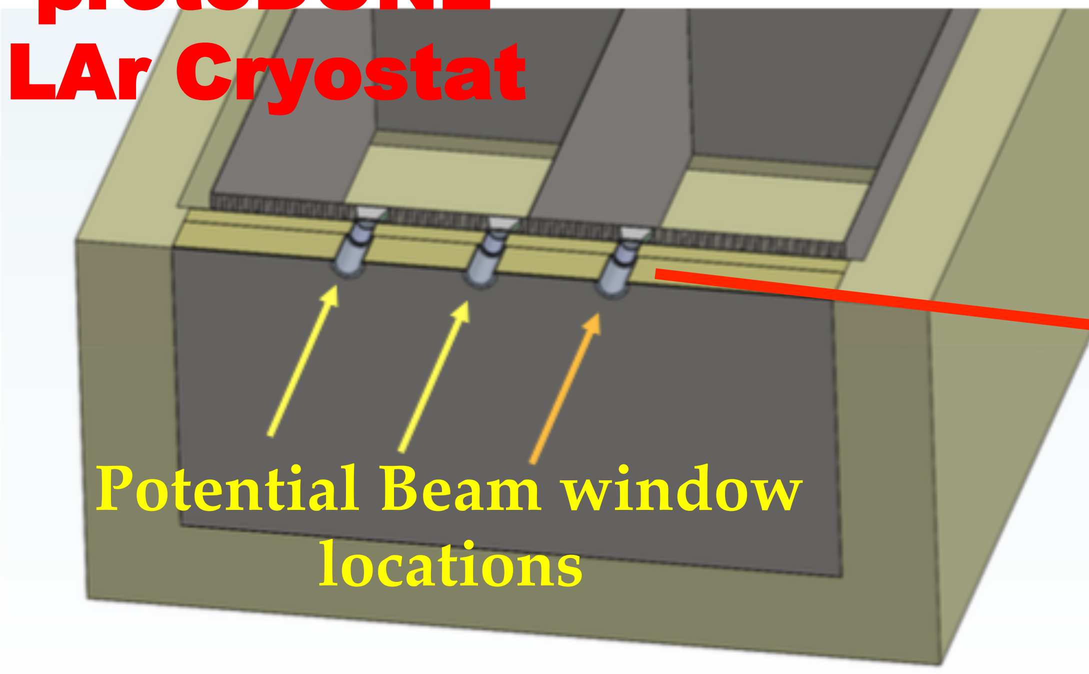




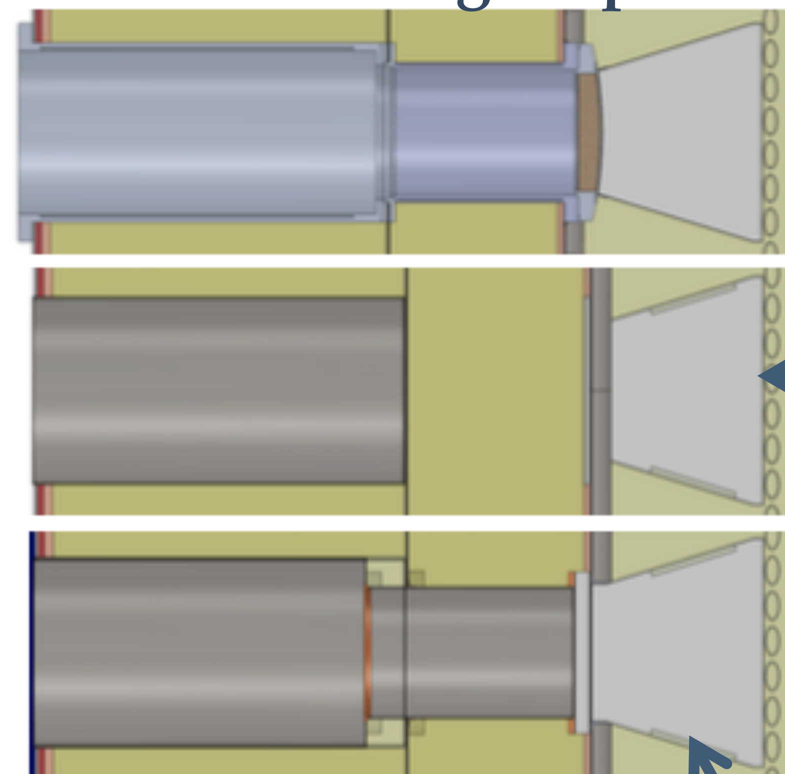
Beam Window Design

Tim Loew (LBNL)

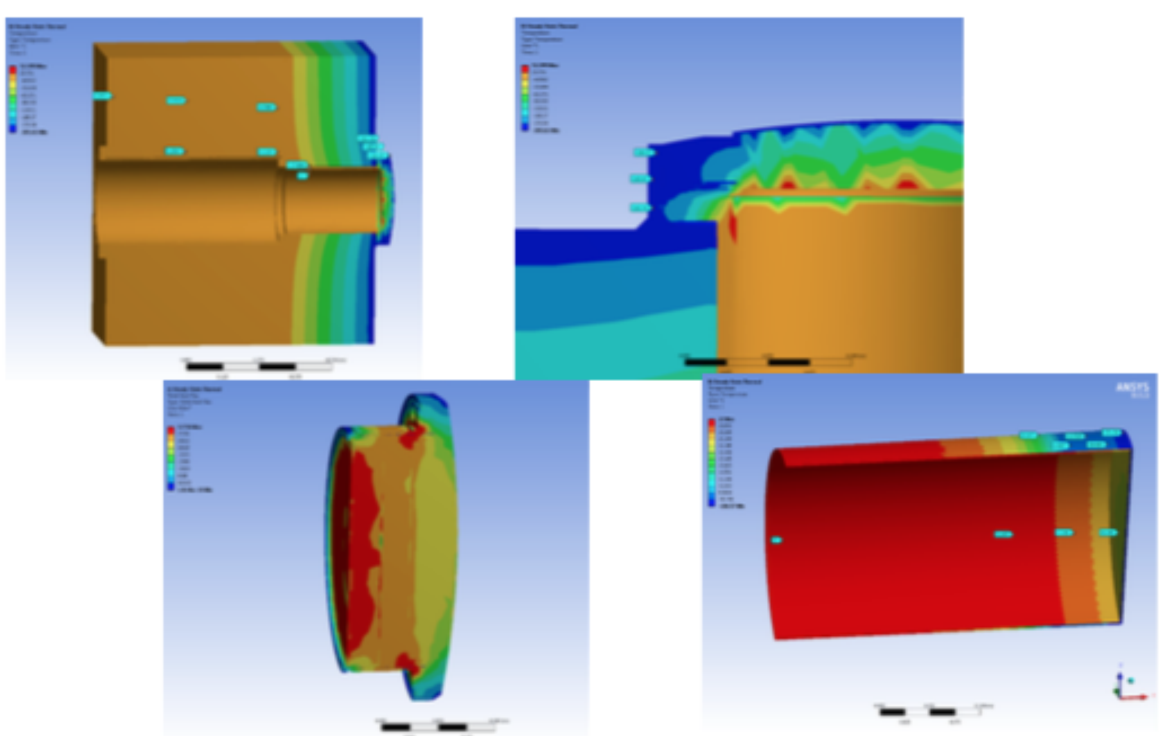
protoDUNE LAr Cryostat

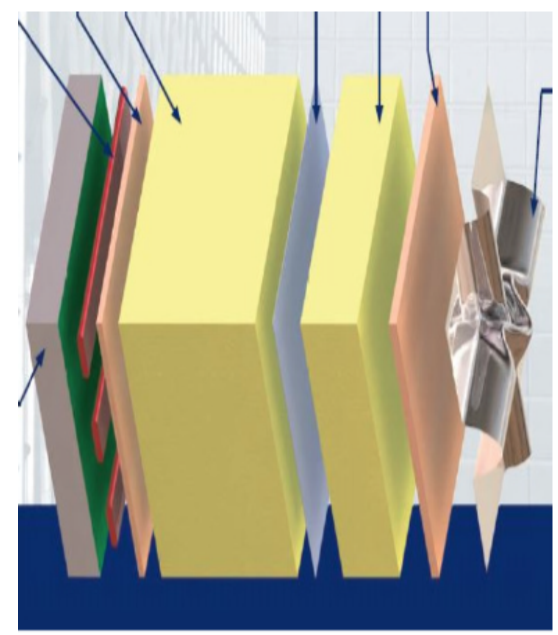


3 Window Design Options



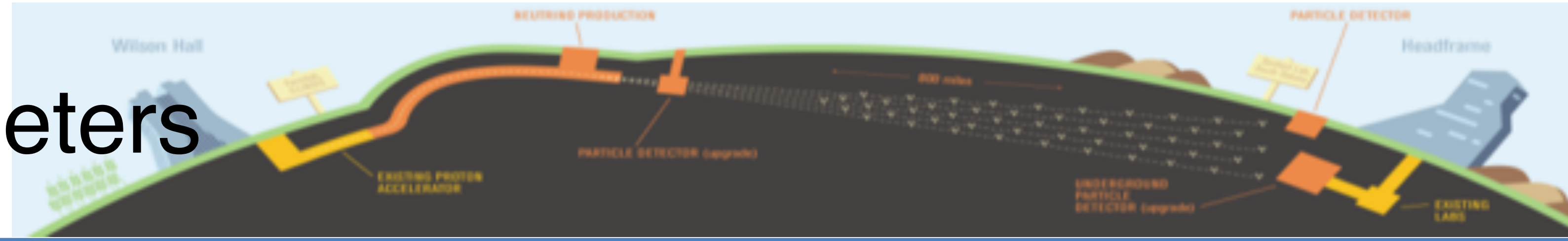
Structural/thermal FEA





Cryostat Insulation Layers

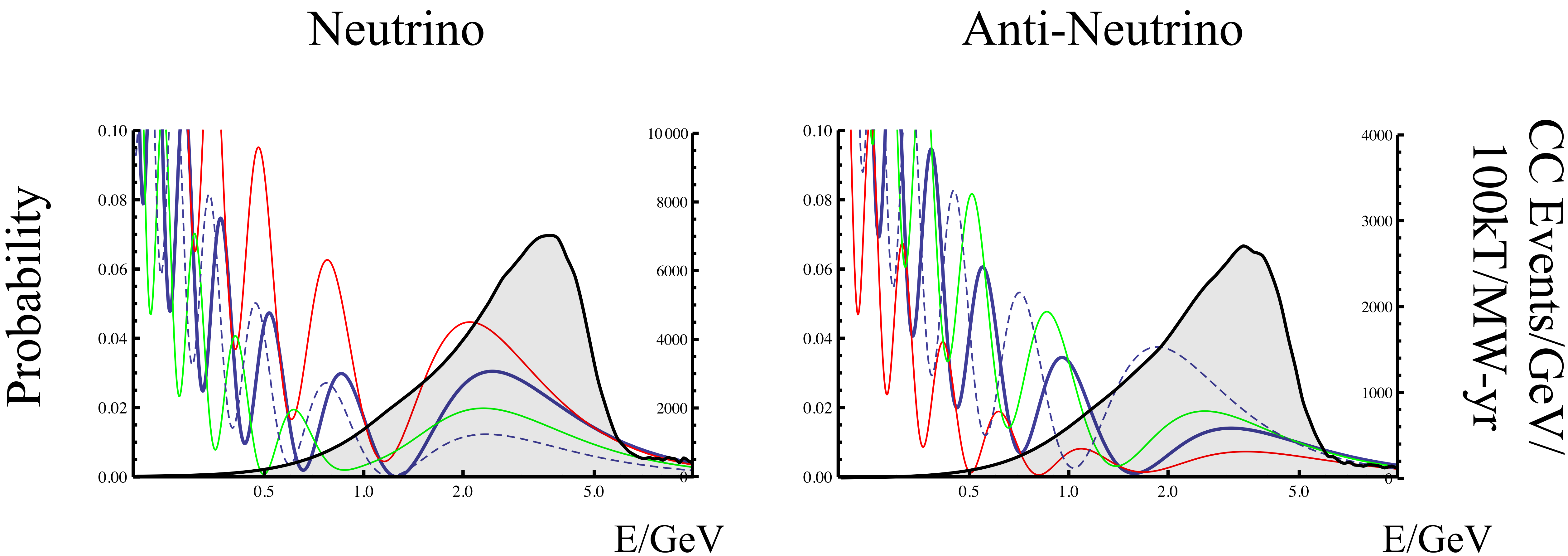
LBNF/DUNE Draft Parameters



- Wide band neutrino beam from FNAL
    - protons: 60-120 GeV, 1.2 MW; upgradable to 2.1-2.4 MW
    - 10 μS pulses every 1.0 to 1.33 sec depending on P energy&power.
    - Neutrinos: sign selected, horn focused, 0.5 - 5 GeV
    - 1300 km thru the Earth to Sanford Underground Research Facility.
- Liquid argon TPC parameters
    - 4 modules of 10kt fiducial at 4850 ft level. cosmics ~0.1Hz, beam~10k CC/yr
    - drift ~3.5 m, field: 500 V/cm, module ~(14m(H)X 14m(W)X40m(L))
    - readout: x,u,v, pitch: 5 mm, wrapped wires, ~150 APAs, 384k chan per mod.
    - Max Yield: ~9000 e/mm/MIP, 10000 ph/mm/MIP. 1 pe/10 MeV
    - As R&D proceeds design may evolve from single phase to double phase.
- near detector parameters
    - distance ~574 m, ~3M events/ton/MW/yr
    - Magnetized Fine Grained Tracker (8 ton) with ECAL, and muon id.
    - Supplemented by a small LARTPC (few tons) or gas TPC.

Scale of project is dictated by physics. Beam and ND and FD detectors require high technology. Project will be done in phases with international partners.

Oscillation and Beam Spectrum



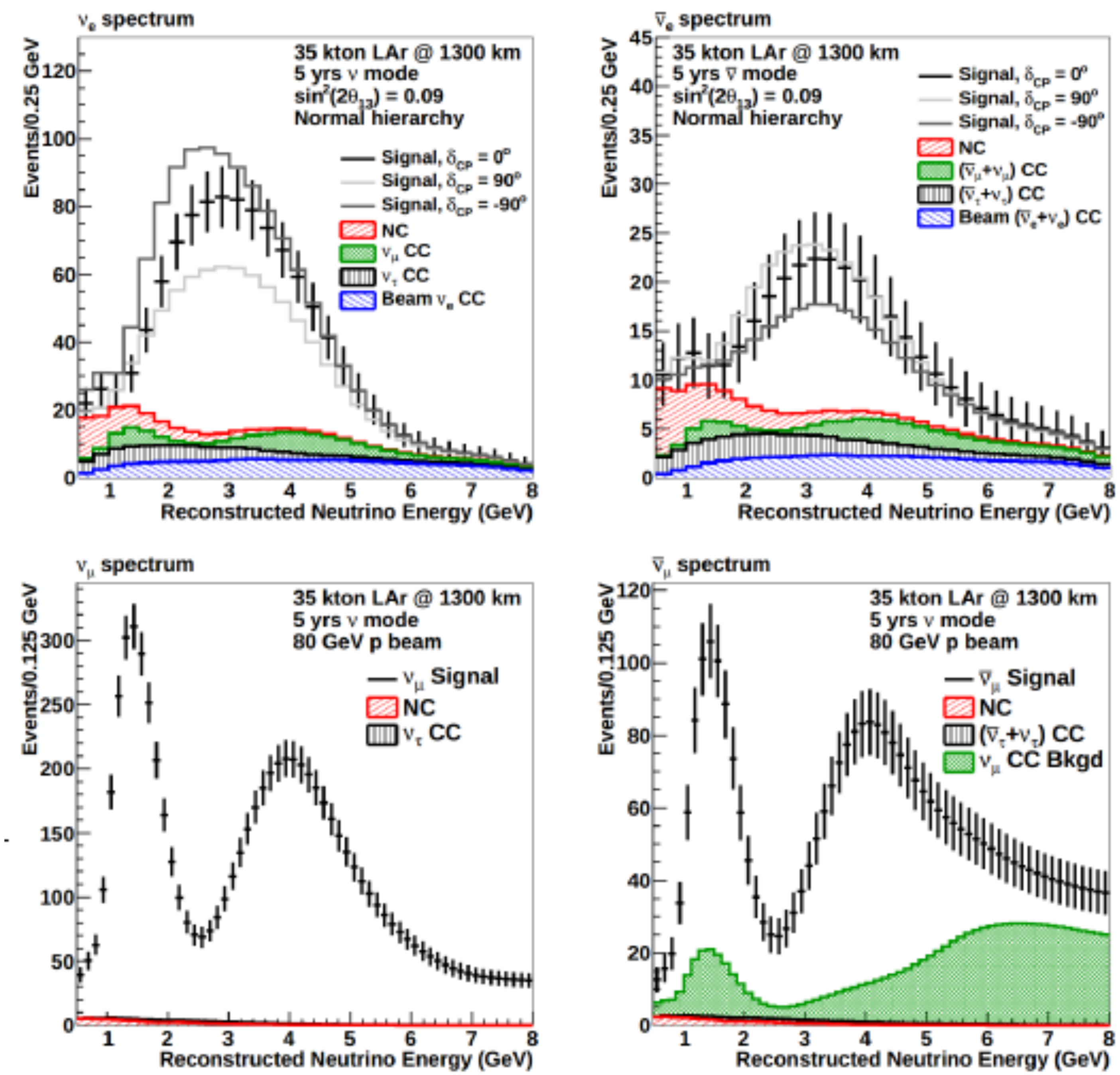
δ_{CP} r:+90, b: 0, g: -90, dashed: Inverted Hierarchy, L: 1300 km

- With 1200 kW of 120 GeV protons from the Main Injector, we have designed a beam optimized for the 0.5 to 5 GeV. (yr=2 10^7sec)
- The baseline and energy allows us to measure the spectral distortion and disentangle MH from CPV.

Event rate and spectra expectation.

Assumptions:
35 kt LArTPC
1.2 MW operation at 80 GeV.
~3 yrs for each polarity.
Normal Hierarchy
δ_{CP}= 0
Rest of the parameters are at best fit from 2012

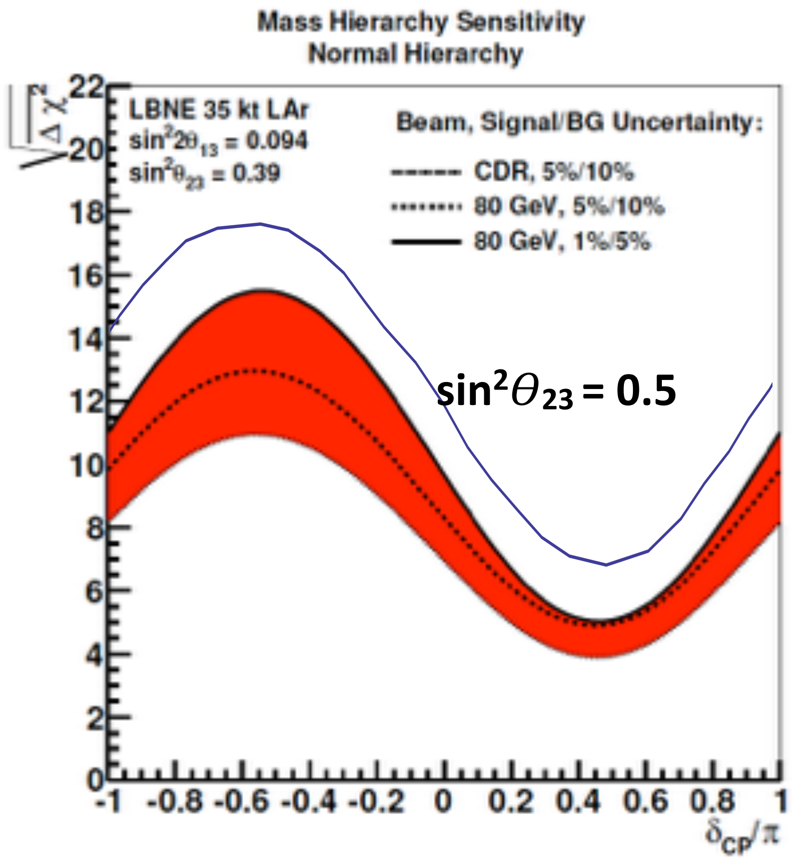
80 GeV Beam	ν mode	$\bar{\nu}$ mode
Signal: $\nu_e + \bar{\nu}_e$	777	189
BG: NC	67	39
BG: $\nu_\mu + \bar{\nu}_\mu$ CC	84	39
BG: Beam $\nu_e + \bar{\nu}_e$	147	81
BG: $\nu_\tau + \bar{\nu}_\tau$ CC	49	32



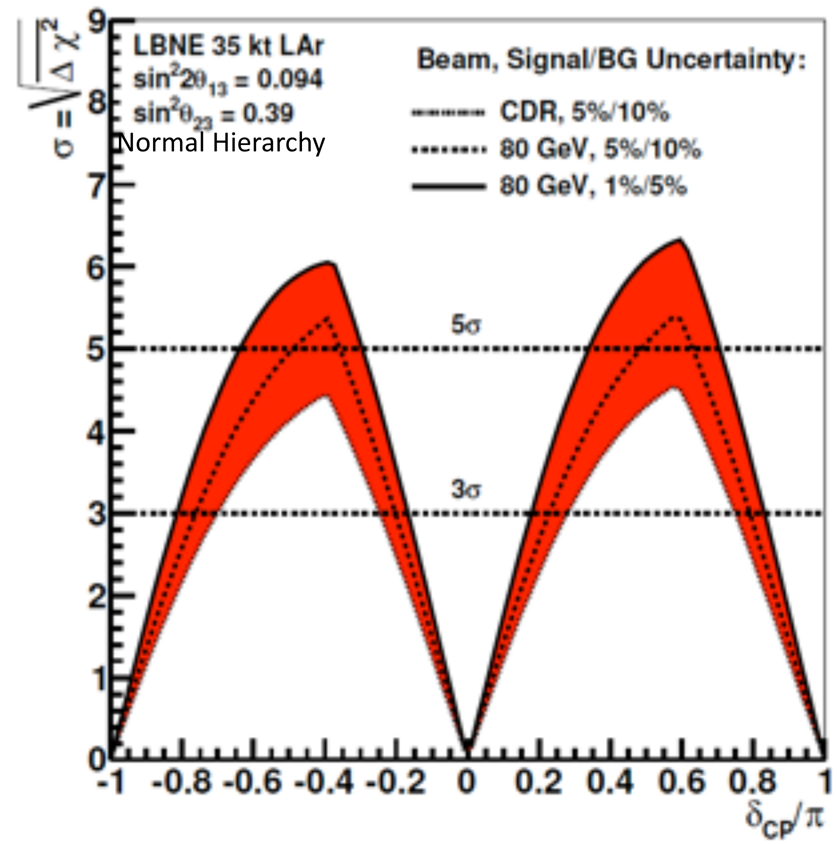
- **At 1300 km full oscillation structure is visible in the energy spectrum. A combined spectral fit provides unambiguous parameter sensitivity in a single experiment. This is a comprehensive experiment.**

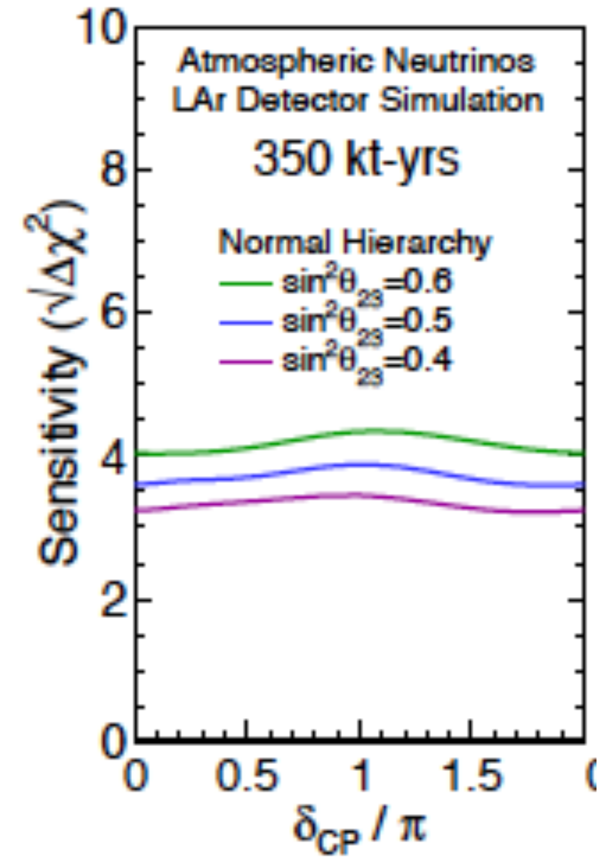
Sensitivity

median sensitivity to reject IH



CP Violation Sensitivity





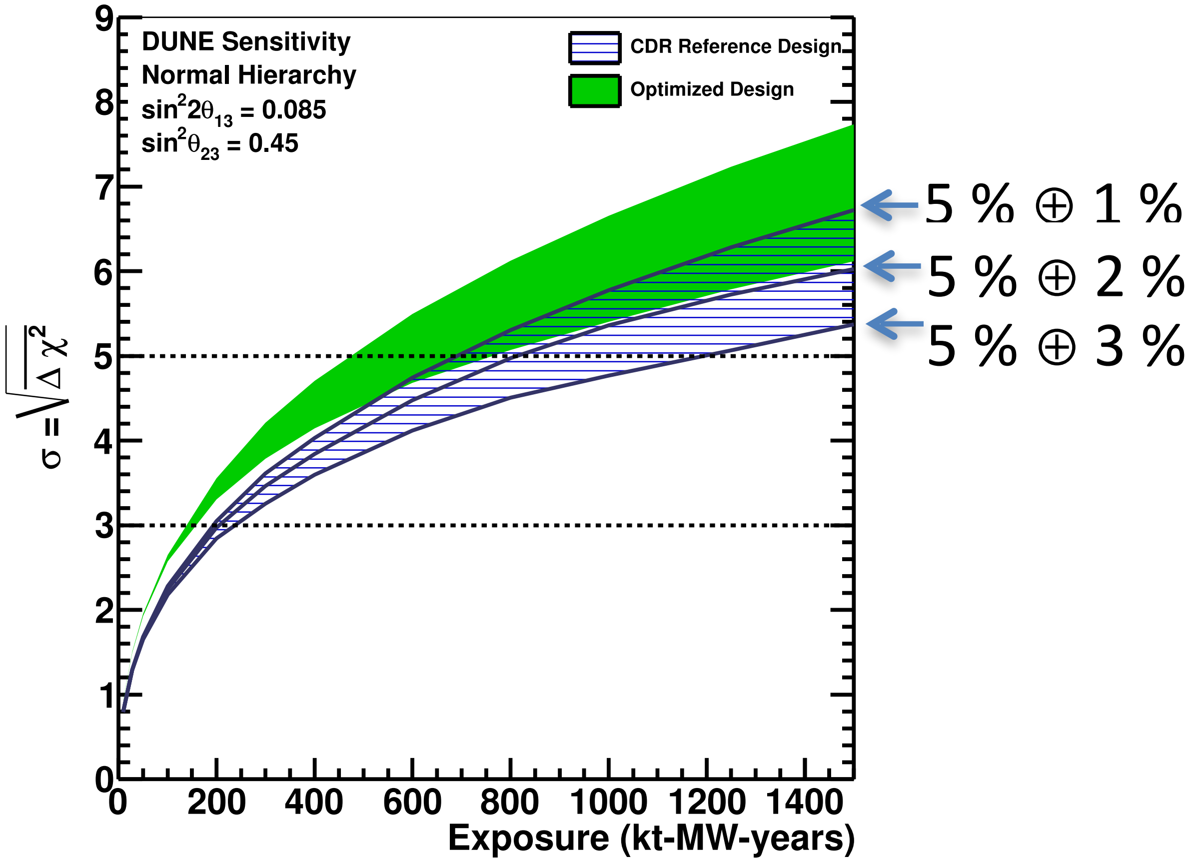
Exposure 245 kt.MW.yr
1.2 MW x 35 kt x(3ν+3ν̄) yr

Parameter sensitivity to $\sin^2\theta_{23} = 0.39 \rightarrow 0.5$

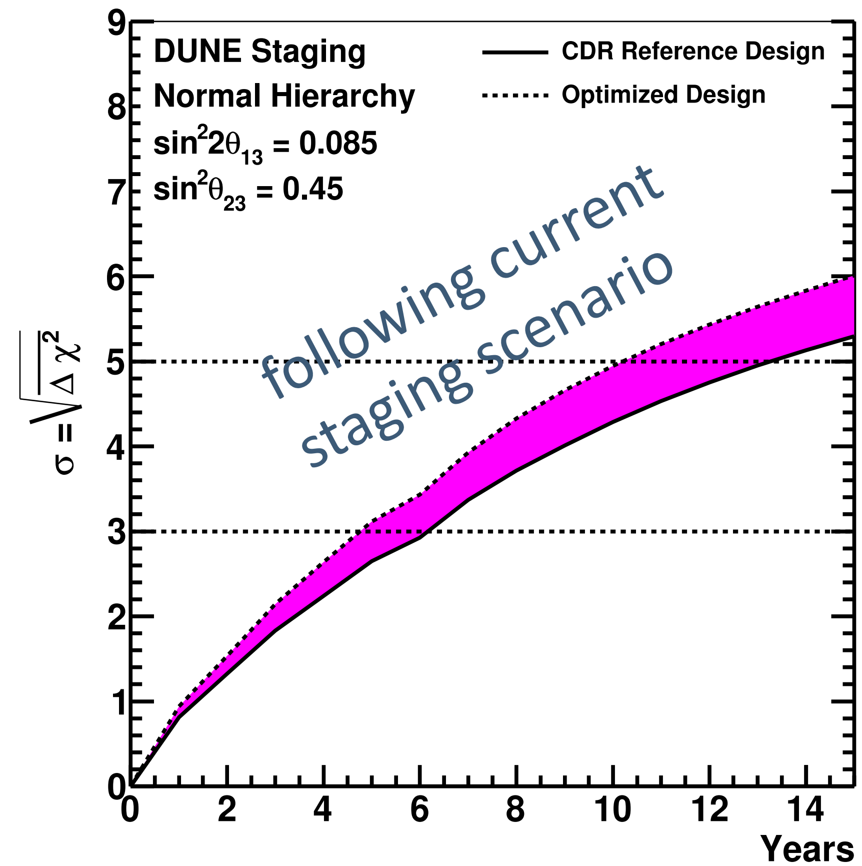
- **For NH versus IH hypothesis testing, following PDG two-hypothesis testing formalism, we find that α = β < 0.13% to be a sufficient criteria. These are probabilities of either rejecting the correct hierarchy or accepting the wrong one, respectively, for the worst case assumptions on parameters.**
- **LBNF/DUNE will produce two independent checks on hierarchy (beam and ATM nus) with median sensitivity >36 (beam) or >9 (atmospheric).**

Propagate to Oscillation Sensitivities
using assumptions for systematics (from the ND)

50 % CP Violation

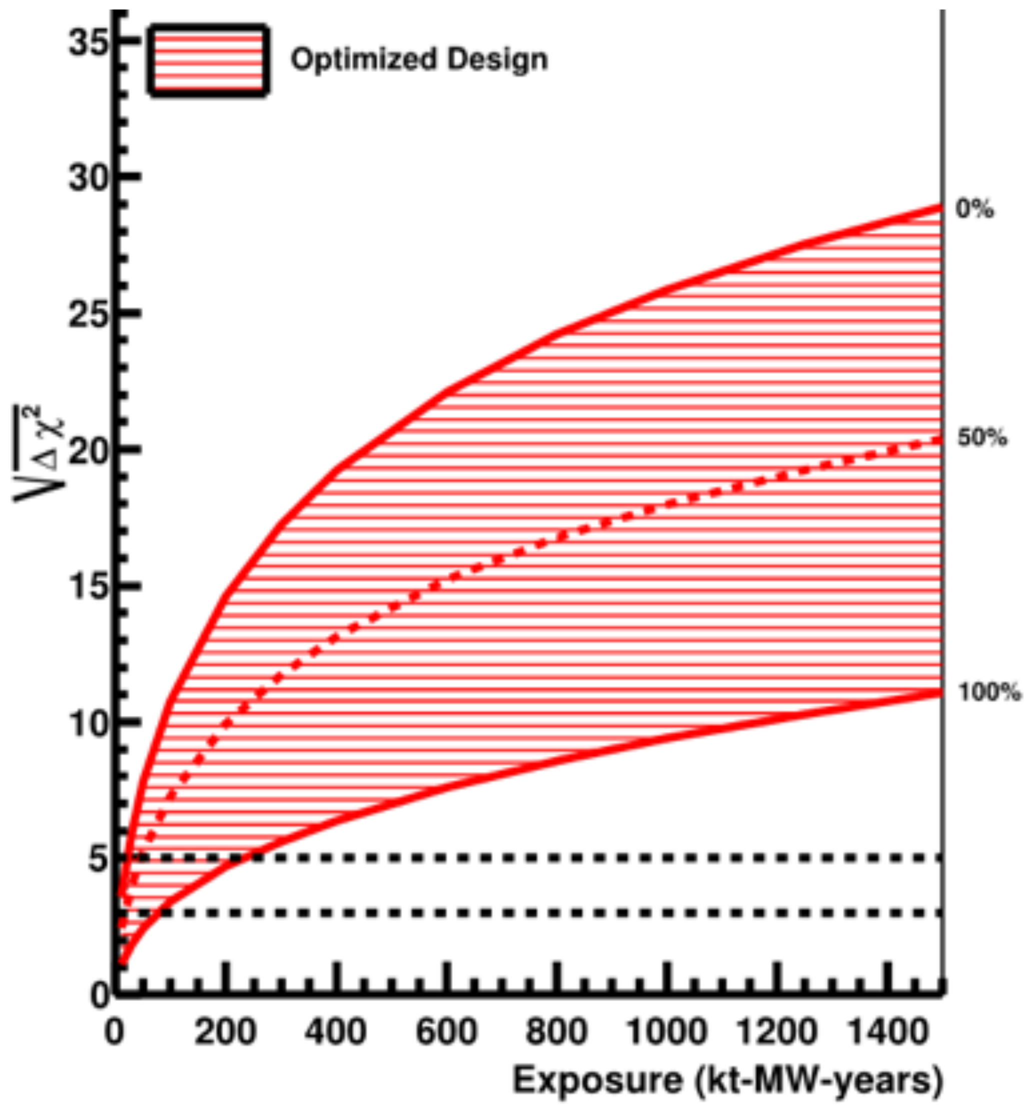


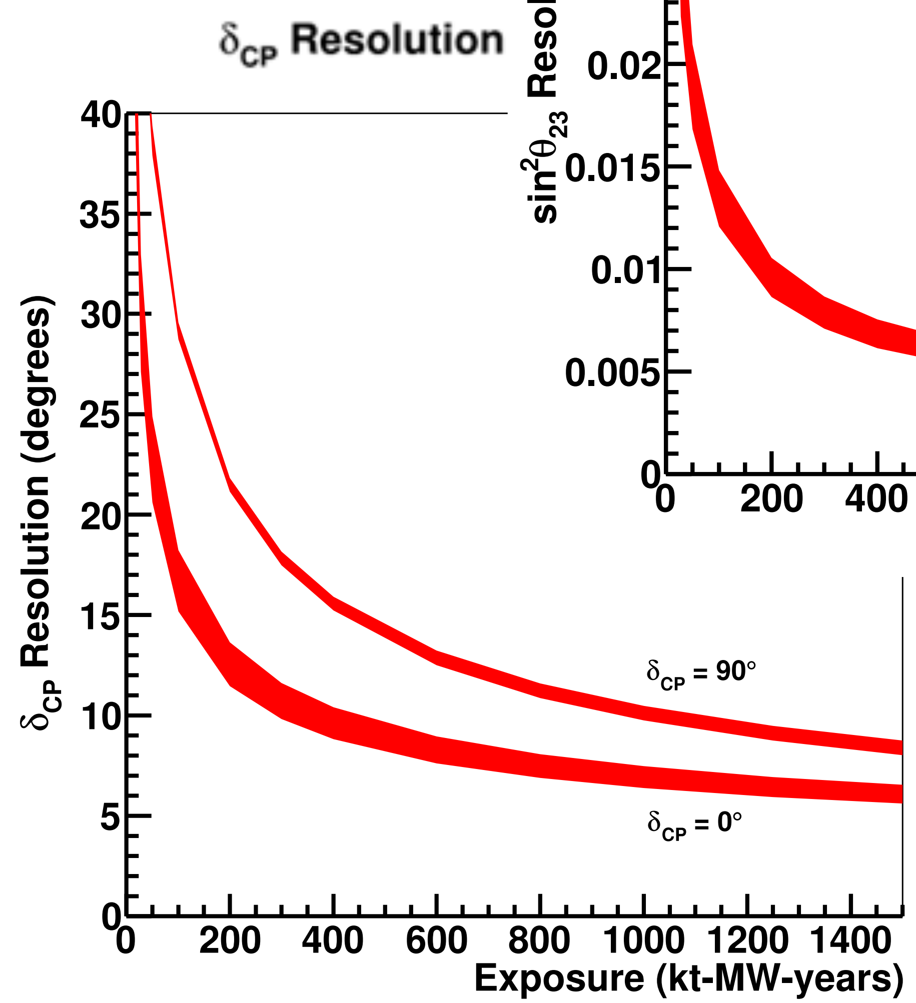
50 % CP Violation Sensitivity

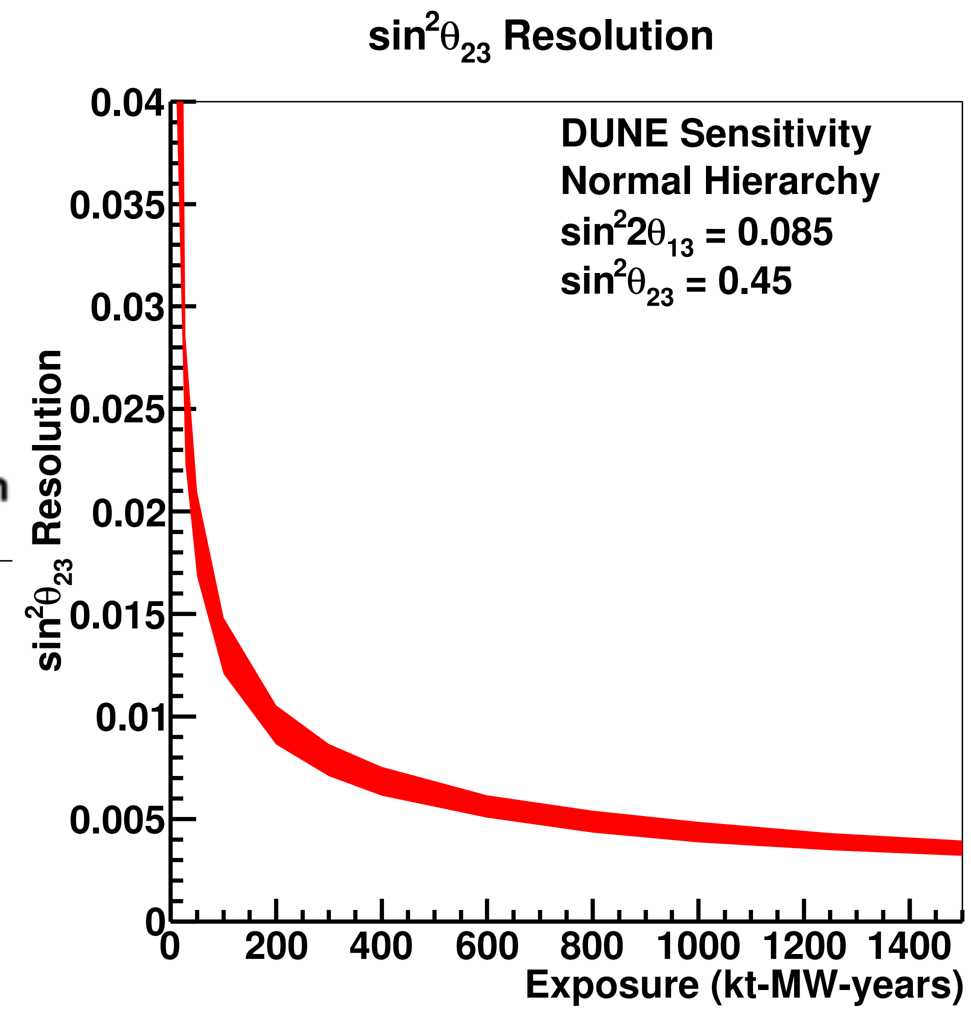


- <3% errors appear realistic with recent progress.
- The systematic precision is required to be better than the expected statistics at each stage of the experiment. High precision is needed after 200kt*MW*yr.
- MH relatively insensitive to systematics; but further study needed.
- MINOS appearance result has achieved better than 5%/5% systematics.

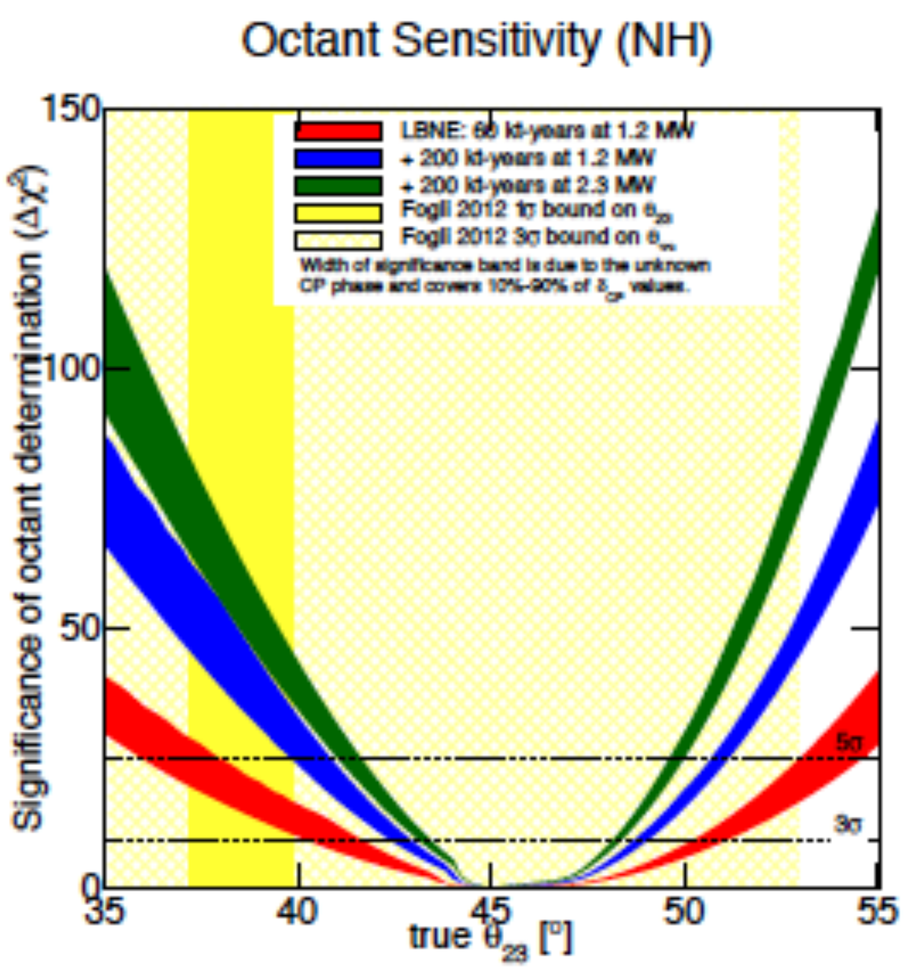
MH, δ_{CP} and $\sin^2\theta_{23}$ Sensitivities

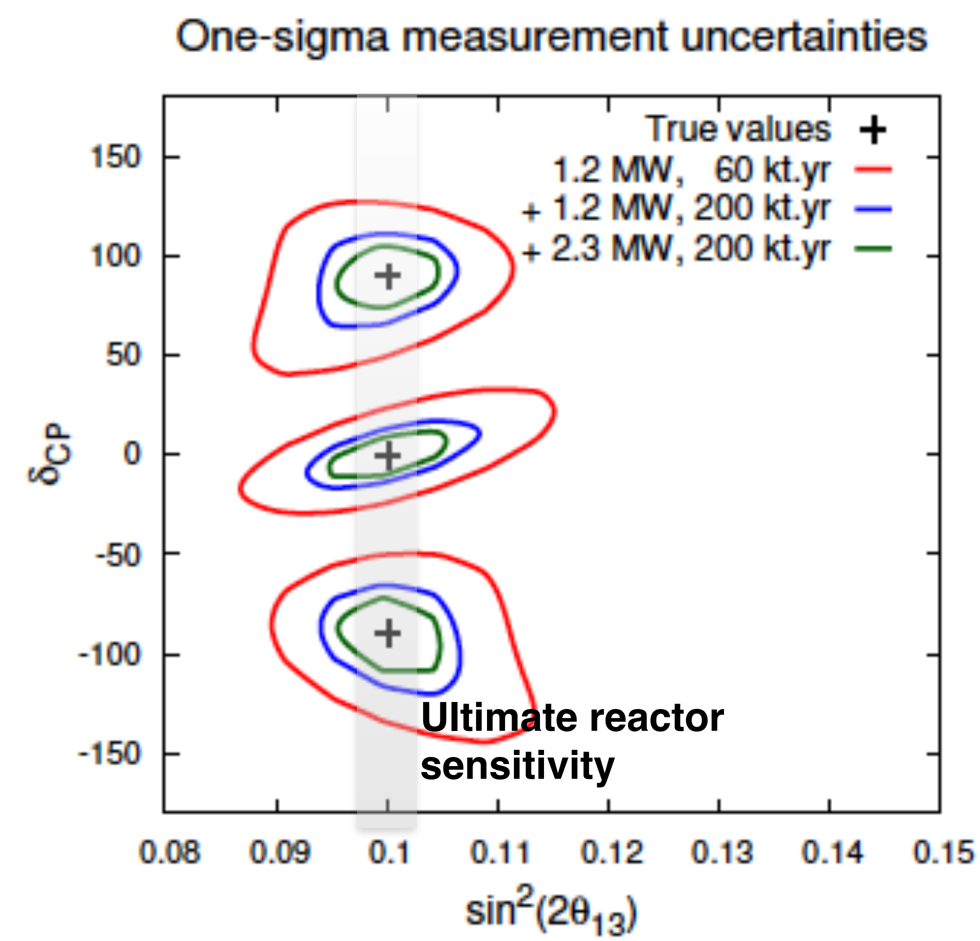






Other measurements for a comprehensive program.





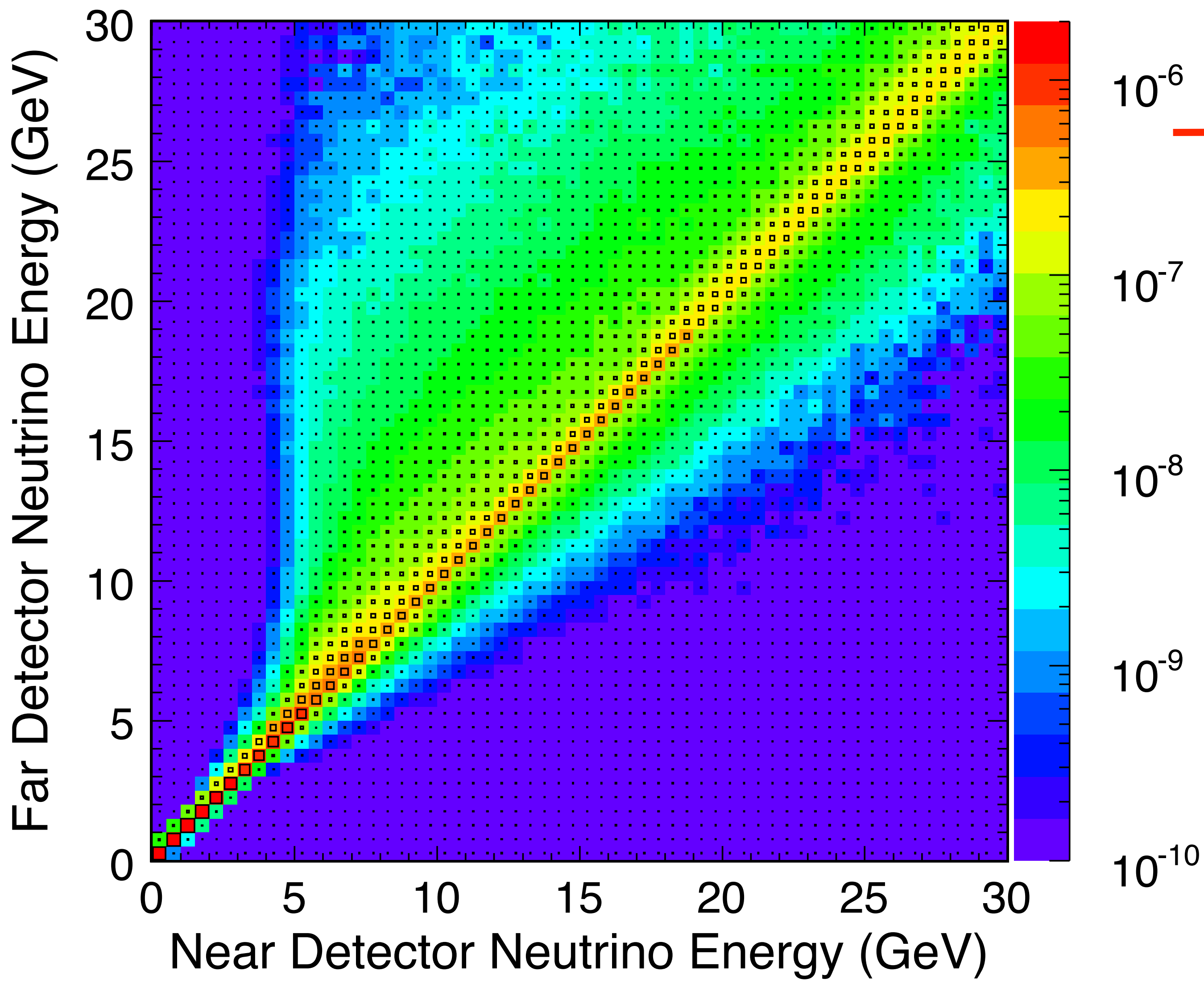
Because of the event rate the program will provide redundant and comprehensive parameter sensitivity for testing the 3-nu model.

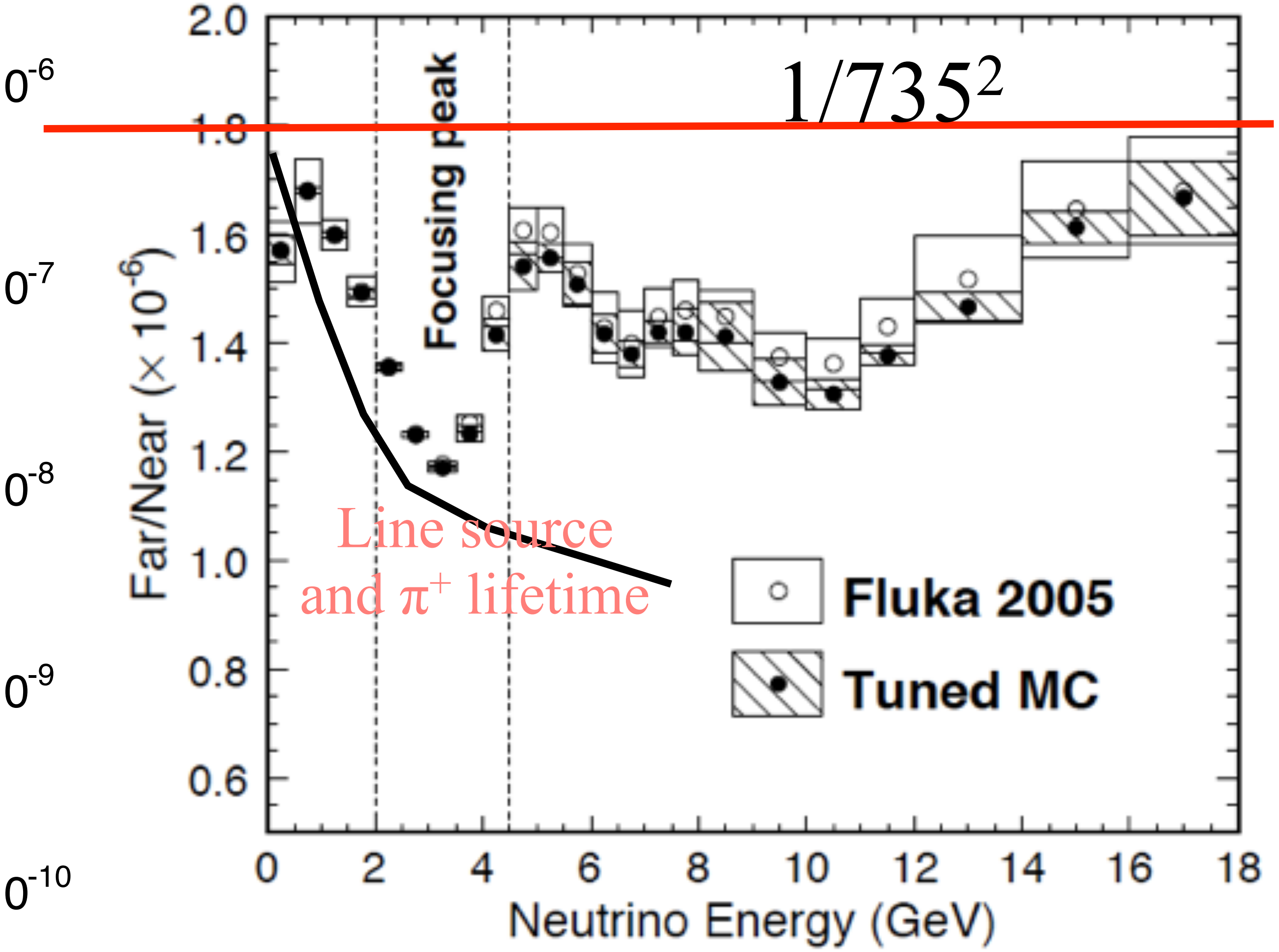
Challenge of the near detector.

- There are two separate tasks that must be performed
  - Obtain enough data to understand the total as well as separate components of the background because they extrapolate differently.
    - Backg due to NC, CC, and beam contamination
    - e.g. CC backg gets modified by oscillations,
    - Precision depends on the statistics of the expected background. (This requirement has already been demonstrated by NuMI experiments and other ~5%)
  - Obtain enough information to understand the event spectrum in great detail so that it can be extrapolated to the far detector.
    - Geometry, Energy scale, Cross section
    - This determines the signal expectation. Must be done precisely for muon disappearance mode. (we need to achieve <3%)

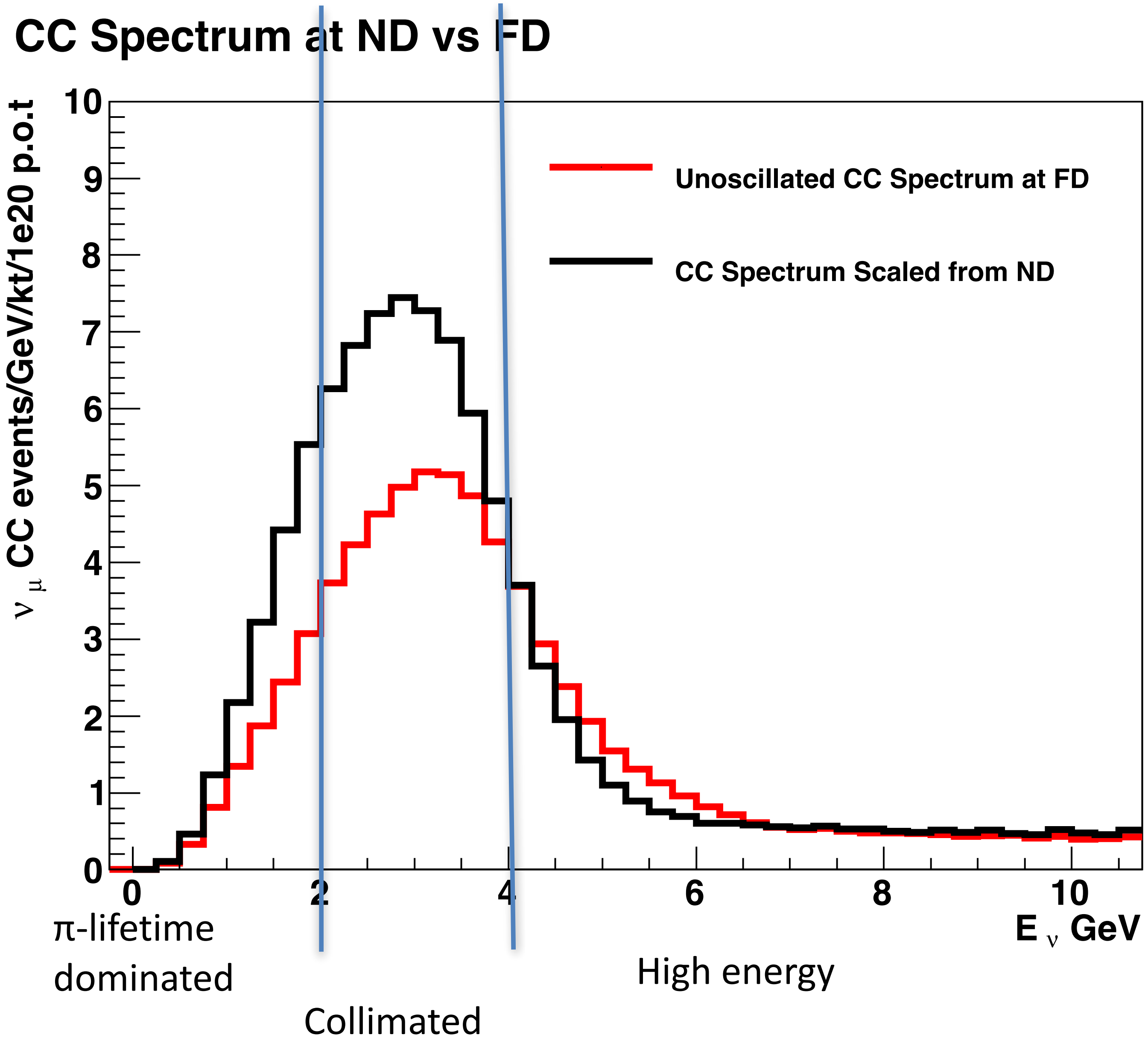
MINOS Extrapolation

- Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- NC and electron-neutrino analyses: Far to Near spectrum ratio for FD prediction of shower events





Challenge: ND Neutrino Spectrum



ND at 574 m
120 GeV protons
NuMI horns
ND scaled by $(0.574/1300)^2$

ND rate ~0.1-0.2 evts/ton 7.5×10^{13}

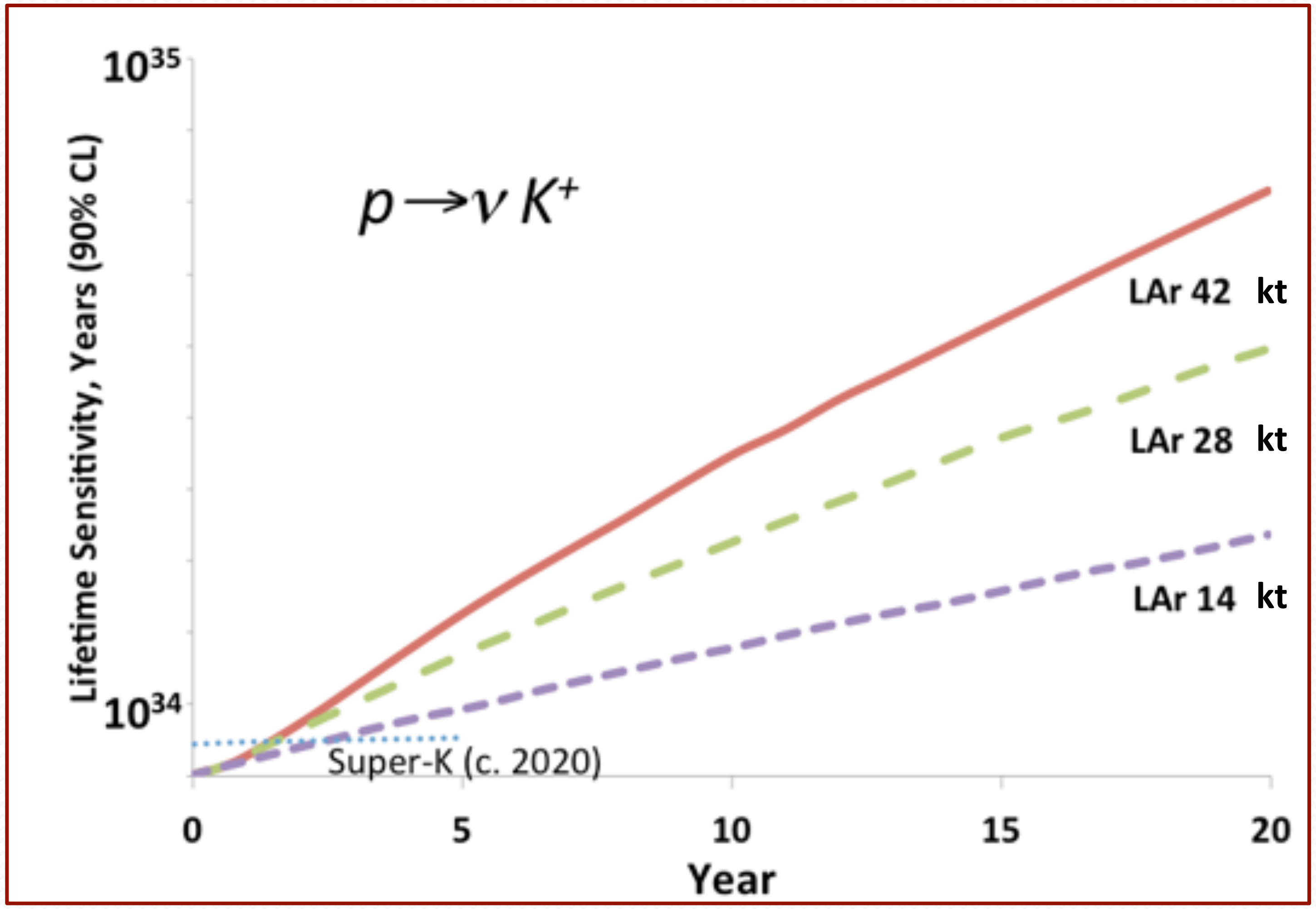
~ 30-40 % corrections must be made by Monte Carlo.

This requires 1) Detailed Beam Geometry Simulation. 2) FD/ND simulations. 3) Reduction of systematics by exploiting correlations.

- ND spectrum is narrower than FD due to hadronic distributions, magnetic focusing, decay kinematics.
- NuMI/MINOS technique: data with beam variations can be used to obtain very precise ND/FD ratio.
- **NEW IDEAS ARE NEEDED.**

Proton Decay

In Liquid argon the Kaon will travel ~13 cm



The key enabling issue is depth. The minimum depth required depends on active vetos if possible.

A depth at 4850 ft level would eliminate any risk.

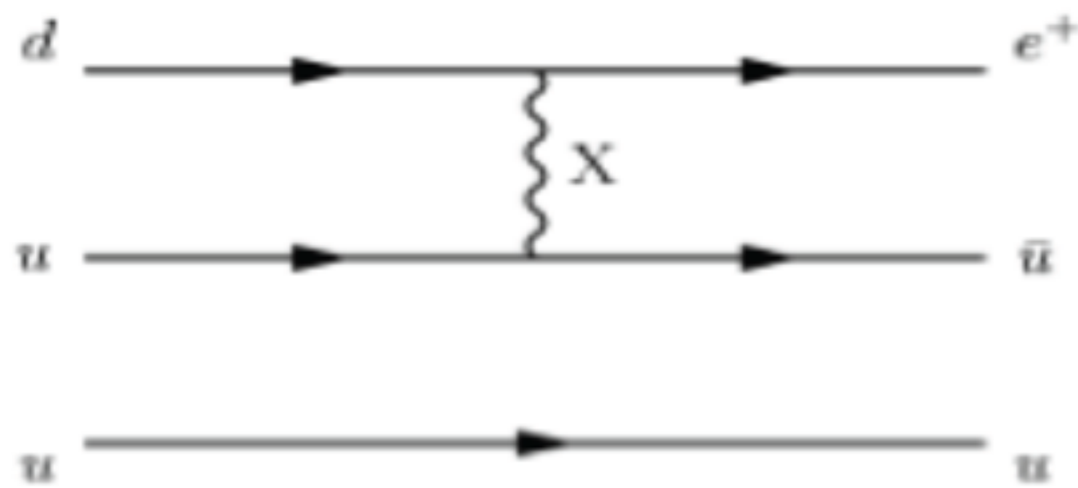
What new justification can be made for this search, esp. regarding a LAr detector ?

- LAr has high efficiency for SUSY-favored decay modes
- High spatial precision and energy resolution enable reconstruction of many potential decays modes
- Much more work is possible here.

Mode	Efficiency	Background Rate (evts/100 kton-y)
	B-L	
$p \to e^+\pi^0$	45%	0.1
$p \to \nu K^+$	97%	0.1
$p \to \mu^+ K^0$	47%	< 0.2
	B+L	
$p \to \mu^-\pi^+K^+$	97%	0.1
$p \to e^+K^+$	96%	< 0.2
	$\Delta B = 2$	
$N\bar{N} \to n(\pi)$	TBD	TBD


ROBERT RATHBUN WILSON
Vast New Global Collaboration has accepted the plan we put forth for Deep Underground Neutrino Experiment.

$(X^{\pm 4/3}, Y^{\pm 1/3})$ GUT Mediated Proton Decay



$p \rightarrow e^+\pi^0$, $e^+\omega$ or $\rho^0 \ldots \pi^+\nu$..

Similarly, $n \rightarrow e^+\pi^-$ (via $Y^{\pm 1/3}$)

Isospin: $\Gamma(n \rightarrow e^+\pi^-) = 2\Gamma(p \rightarrow e^+\pi^0)$

$\Gamma(p \rightarrow \pi^+\nu) = 2\Gamma(n \rightarrow \pi^0\nu)$

Bill Marciano

☼Challenge: Can we lower the backgrounds for all modes that include a pion and enhance the sensitivity in a liquid argon detector for Pion modes ?

Proton decay and LHC have deep complementarity: LHC SUSY searches are increasing the mass making the Pion modes more observable.

Supernova burst

$$e^- + p \rightarrow n + \nu_e$$

LAr mainly sensitive to electron neutrinos.
(water is sensitive to anti-electron-neutrinos)

A large theory effort is underway to understand neutrino related dynamics of the supernova. Both oscillations, mass, and self-

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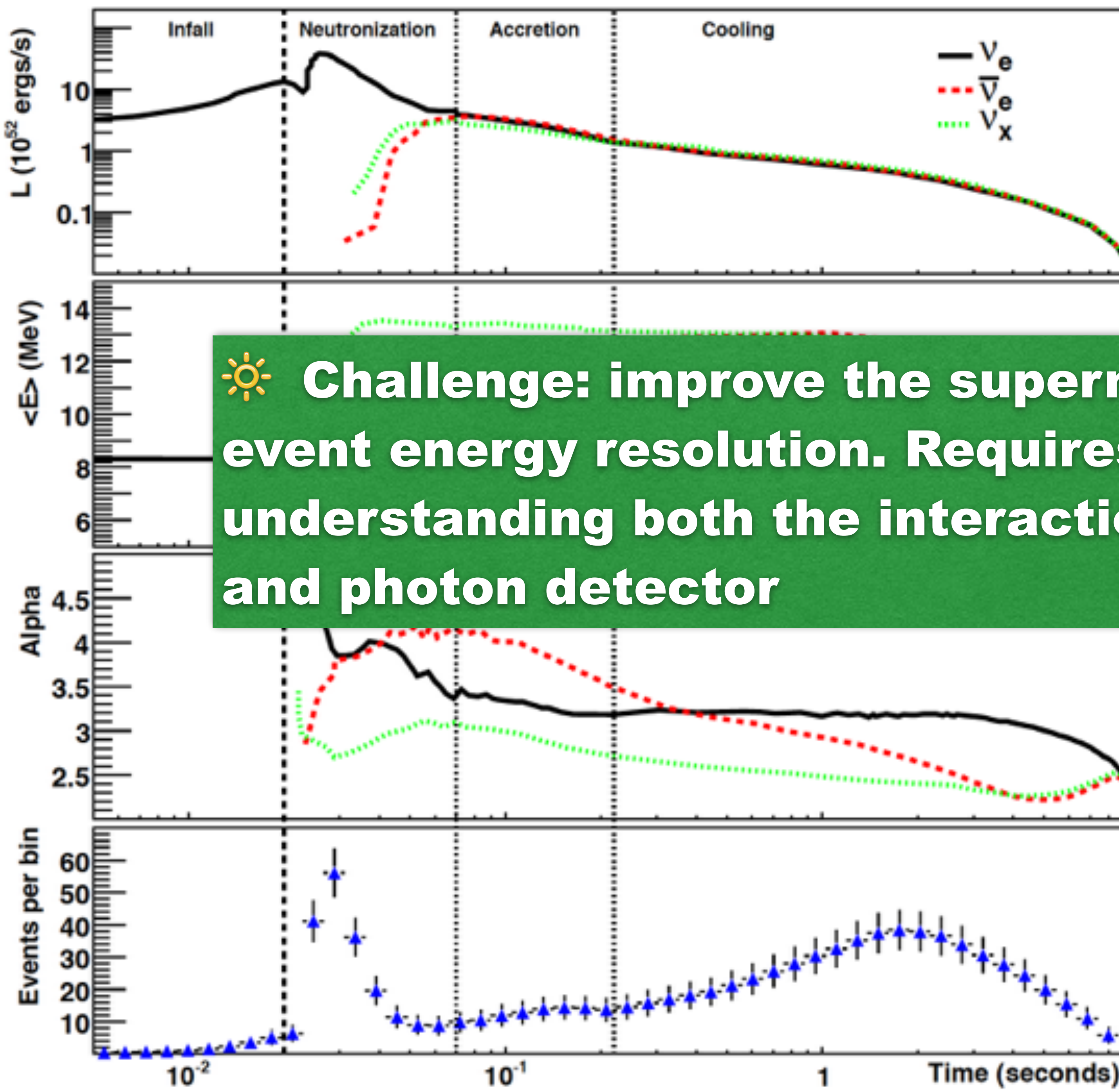
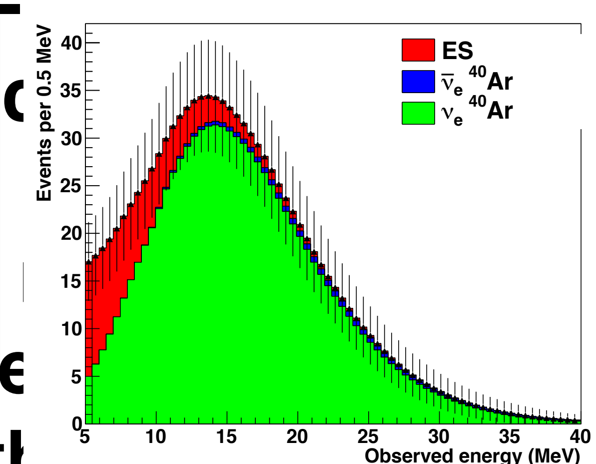


Challenge: improve the supernova event energy resolution. Requires understanding both the interaction and photon detector



Precision astrophysics and cosmology needs precise laboratory data on neutrinos so that correlations can be resolved.

Estimated rate: ~3000 evts @ 10 kpc for 34 kt LAr TPC

Physics Opportunities

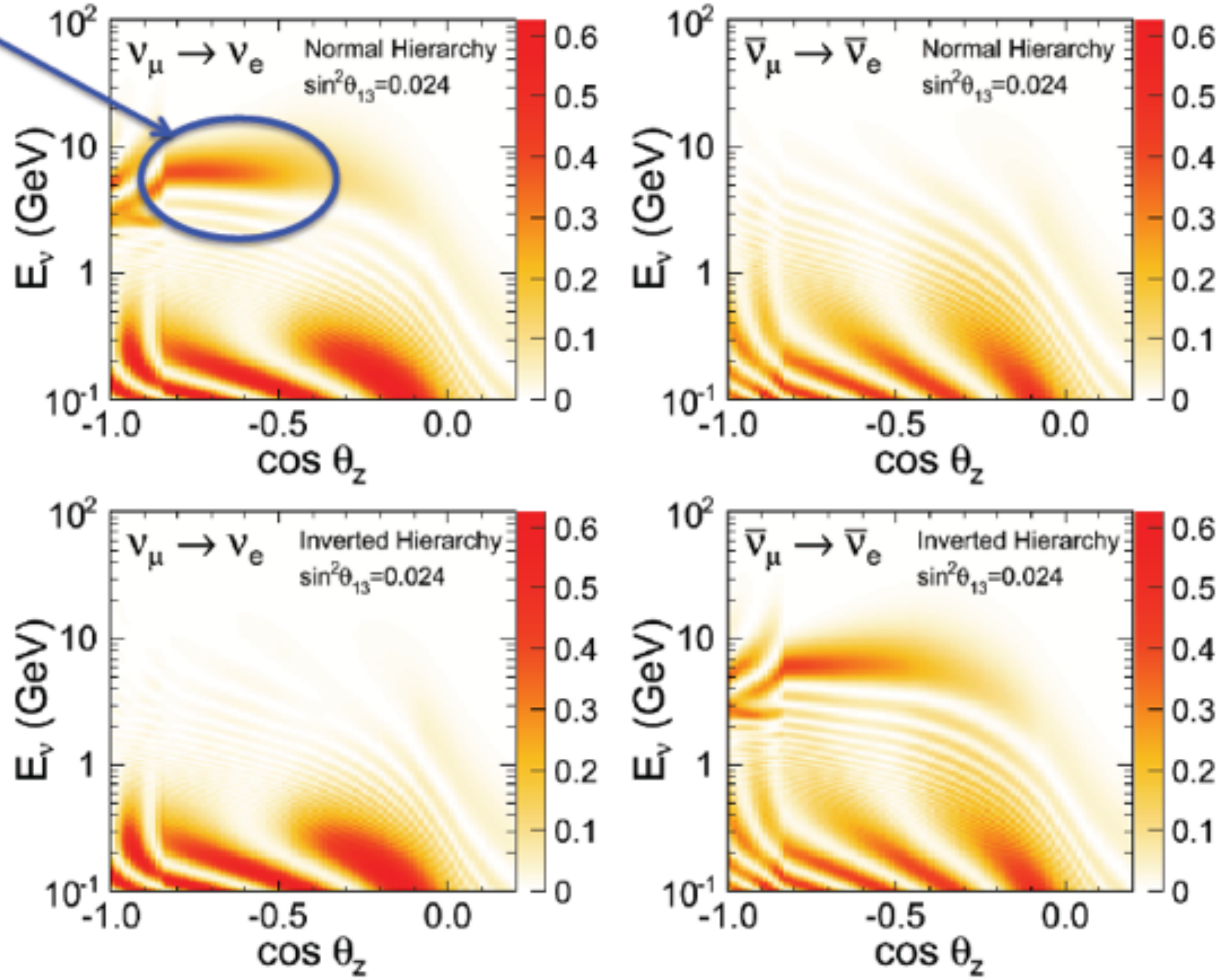
Atmospheric neutrinos

Large θ_{13} means MSW enhancement for 2-10 GeV upgoing neutrinos (NH) or anti-neutrinos (IH).

All flavors present in oscillated flux.

Possibilities for tau appearance.

Ideal detector:
- Excellent flavor ID
- Energy resolution
- Angular resolution
- Nu/nubar separation
- Big!!

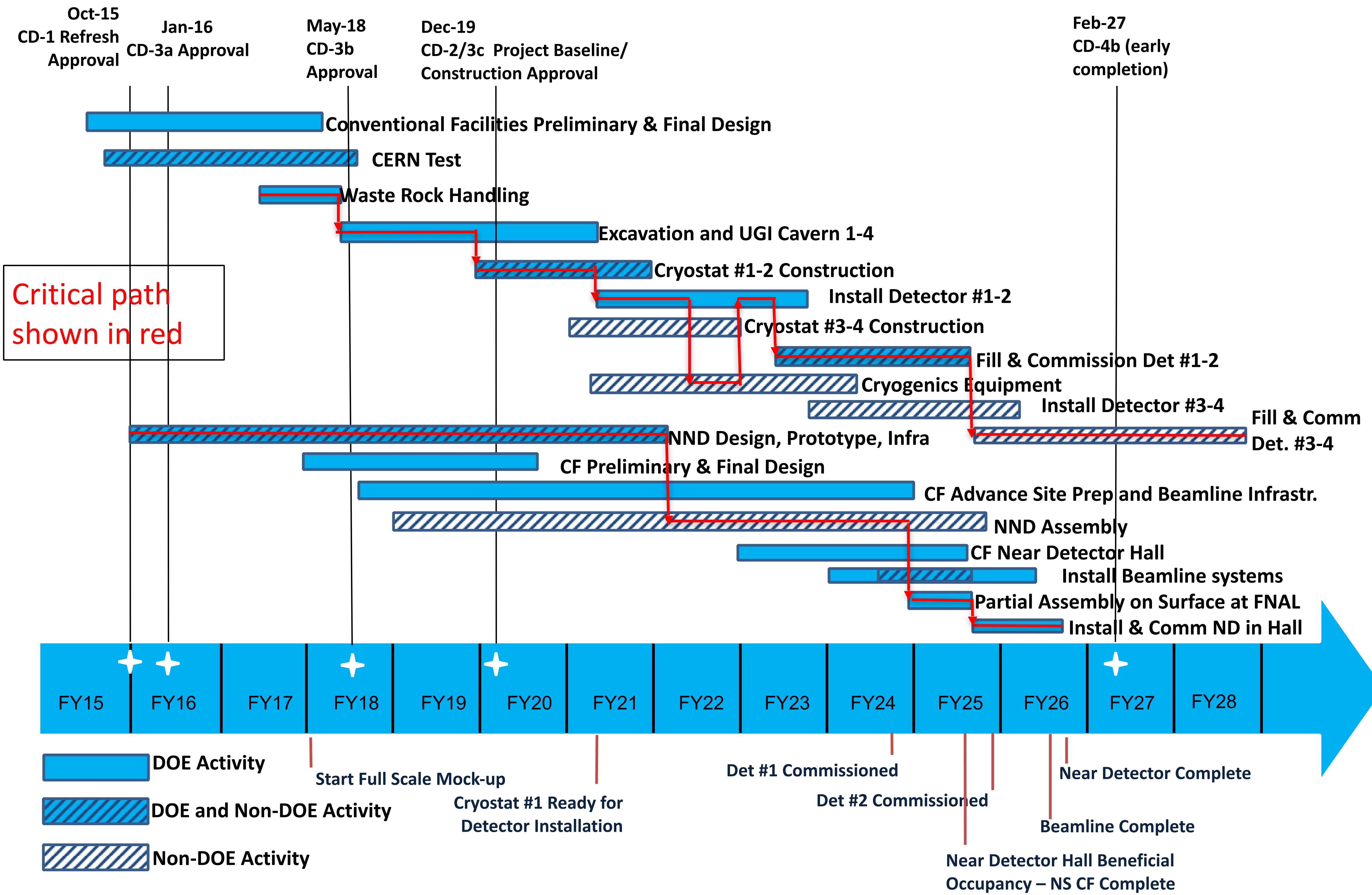


~48000 evts/ 400kt*yr

Andy Blake / Hugh Gallagher ISOUPS - May 26, 2013 Slide 3/27

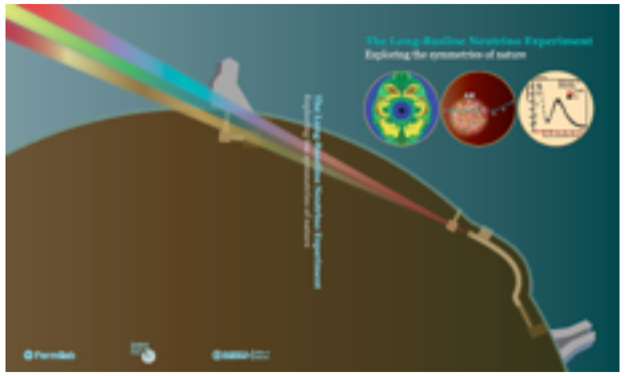
- **The atmospheric data can be used to either enhance parameter sensitivity in combination with beam or use the beam measurements to look for new effects. This is similar to INO, but has less target mass.**

LBNF/DUNE Schedule Summary Overview



Conclusion

- Scientific motivation and scale of the next generation long-baseline neutrino oscillation experiment is well-known. LBNF design meets the requirements for a comprehensive experiment aimed towards CP violation in the neutrino sector.
- The US has unique assets to host this program given the availability of high intensity accelerator
  - 700 kW upgrade in commissioning
  - 1.2 MW by the time of LBNE start
  - Further upgrades to >2.3 MW
- An operating world-class Sanford Underground Research Facility (Dark Matter and Double Beta Decay experiments have started at 4850L)
- Committed to make this a fully international scientific program.



- Snowmass detailed-whitepaper arXiv:1307.7335
- Brazil can play a large role in this project bot intellectually and by developing the photon detector.